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Control Technologies for Particulate and Tar Emissions from Coal Converters

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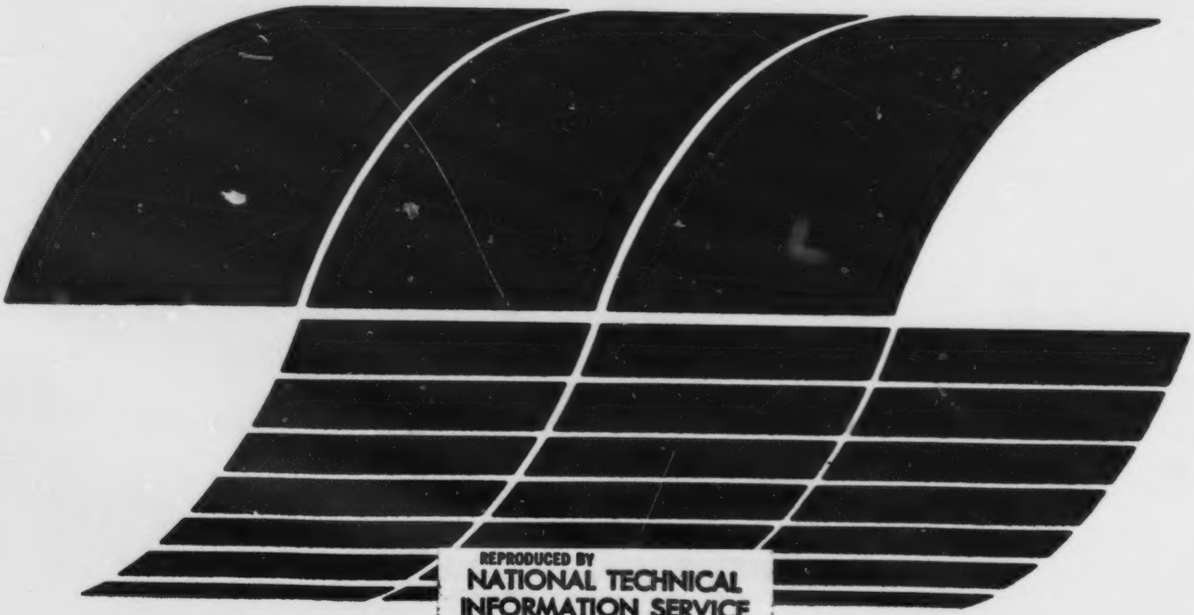

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16. ABSTRACT The report gives results of a characterization of solid and tar particulate emissions in raw product gases from several types of coal gasifiers, in terms of their total quantities, chemical composition, and size distribution. Fixed-bed gasifiers produce the smallest particulate loadings, about 3 g/cu m. Entrained-bed gasifiers produce the largest, about 110 g/cu m. Control technologies for particulate emissions were assessed with respect to the limitations of the control device and to existing and proposed regulations. Fabric filters were not suitable where tar particulates were found or at higher than 300 C. Electrostatic precipitators operated as high as 1100 C. Rotary cyclones showed the widest range of applicability. Conventional cyclones were most economical for particles larger than 50 microns. Solid and tar particulate emissions collected for 250,000 scfd of a medium-Btu gas contained up to 1.6 million kg of particulate containing about 400 ppm of organic compounds which were benzene extractable. Naphthalenes and three-ring aromatic compounds each showed compositions of about 15 ppm. More than a dozen other classes of compounds were identified in the analyses of the organic material deposited on the particulate matter.

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Coal Gasification		Stationary Sources	13H	
Tars	Cyclone Separators	Particulate	07C	07A
Dust		Fabric Filters	11G	
Fabrics			11E	
Gas Filters			13K	

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ABSTRACT

Raw product gases from coal converters generally contain particulates and tars which must be controlled to a level compatible with environmental regulations. Control technologies for removing particulates and tars from product gases were identified and evaluated.

Particulate and tar emissions in raw product gases from several types of coal gasifiers were characterized in terms of their total quantities, chemical composition, and size distribution. The emissions data were organized according to generic gasifier type, with fixed, fluid, and entrained-bed gasifiers being considered. The design and operating features of each identified control technology were described, with emphasis on characterizing collection efficiencies as a function of particle size and other parameters. These data were also organized into generic categories such as cyclones, wet scrubbers, electrostatic precipitators, fabric filters and granular bed filters.

The applicability of each of the identified control technologies was assessed with respect to the generic gasifier types for combined cycles and gas-fired boilers. These assessments were based on existing and proposed environmental regulations and process requirements for product gas purity. The fate of the particulate and tar emissions was assessed in the purified product gases, liquid effluents, and solid wastes or sludges. Gaps in the data base required for these assessments were identified.

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SECTION I

INTRODUCTION

1.1 BACKGROUND

The energy supply problems of the United States and most of the major industrialized nations are well-known and documented. Current projections indicate that the world demand for petroleum and natural gas will exceed supply sometimes during the 1980's. One obvious approach to increasing domestic fuel supplies, and consequently to reducing demand for imported gas and oil, is to utilize the vast coal resources of the United States to produce synthetic oil and gas.

In recent years, the electric utility and industrial sectors of the economy together accounted for about 55 percent of the energy consumption in the United States. Natural gas and petroleum supplied about 80 percent of the industrial energy consumption and 30 percent of the utility consumption. The use of coal-derived fuels to replace natural gas and petroleum in these areas could have important economic benefits to the United States, in addition to reducing the nation's dependence on foreign, unreliable sources of energy. Such coal-derived products might be employed in a wide variety of end uses, such as industrial process heat, industrial and utility boilers, gas turbines, and reducing or synthesis gas for various industries.

In the case of coal-derived product gases from coal gasifiers, each particular end use of the gases would have different environmental regulations and/or process requirements governing the allowable particulate and tar levels in the product gases. Thus, the use of coal-derived product gases to replace natural gas and oil on a large scale will require adequate control technology to remove tars and particulates from the product gases to levels compatible with the various possible end uses. The overall objective of this study was, therefore, to assess the applicability of alternate control technologies both commercially available and under development for the removal of particulates and tars from coal-converter product gases.

The study described herein was performed under EPA Contract Number 68-02-2601 for the Fuels Process Branch of the Environmental Assessment and Control Division of the Industrial Environmental Research Laboratory at Research Triangle Park (IERL-RTP).

1.2 METHODOLOGY

The first step in carrying out these control technology evaluations involved the identification and collection of pertinent sources of information. Computerized literature searches covering the Chemical Abstracts, Engineering Index, Pollution Abstracts, U.S. and foreign patents, government publications, and numerous journals were made to identify sources of information. These computerized searches were complemented by thorough library and patent searches. In addition, other EPA contractors, process developers, and equipment vendors were contacted for relevant data.

After reviewing the identified sources of information, appropriate data therefrom were employed to carry out several sub-tasks, as summarized briefly below.

The initial sub-task involved the characterization of the raw product gases from fixed, fluid, and entrained-bed gasifiers, with emphasis on the particulate and tar contents of the gases. Gasifier emission data were characterized in terms of total particulate and tar loads, the chemical composition of both the particulates and tars, particle size distribution, and other pertinent exhaust gas parameters. Representative emission factors for the above generic gasifier classes were thereby developed. A second sub-task involved the identification and description of the performance of alternate control technologies for particulates and tars, with emphasis on characterizing the particulate removal efficiency of each control device.

The results of the above two sub-tasks were then employed to assess the applicability of each control technology to the various gasifiers under consideration. Applicability assessments were made for two end uses representing low-to-moderate and high degrees of required particulate removal. Both applicable environmental regulations and process requirements were considered in these assessments.

Another sub-task involved assessments of the ultimate fates of the particulates and tars with respect to their presence in gaseous, liquid, and solid discharge streams. All available data from experimental and commercial installations were employed as the basis for these assessments.

Finally, the data available to carry out the above sub-tasks were reviewed and examined to identify gaps and deficiencies in the available data base and the resulting R & D requirements.

SECTION 2

CONCLUSIONS AND RECOMMENDATIONS

2.1 CONCLUSIONS

Applicability assessments were made for various combinations of particulate control devices and gasifier-end use pairs. These assessments were made for the three major generic classes of coal gasifiers, including fixed-bed, fluid-bed, and entrained-bed, and for two end uses for the product gases. The first end use consists of combined-cycle power generation with the fuel gas combusted in a turbine, which represents a relatively high product gas cleanup requirement. The second end use consists of boiler fuel, which represents a low-to-moderate cleanup requirement.

Detailed applicability assessments were made for the following six generic classes of control devices: (1) conventional cyclones, (2) rotary flow cyclones, (3) venturi (wet) scrubbers, (4) fabric filters, (5) electrostatic precipitators (ESP's), and (6) granular bed filters.

The results of these assessments are summarized in Table 23 of Section 5. Due to the uncertainties in the emission characteristics from the different types of gasifiers, these results are presented in terms of best-case, worst-case, and average (or typical)- case analyses. The worst-case condition represents the estimated upper limit of particulate load, with a relatively high percentage of small particles, which are difficult to remove. The best-case condition represents the estimated lower limit of particulate load with a relatively low percentage of small particles. All available data on the characteristics of gasifier emissions were considered in estimating these upper and lower bounds.

In the case of the combined-cycle end use, fabric filters, venturi scrubbers, and rotary flow cyclones were found to be applicable for at least some gasifiers. The other control devices listed above would not be applicable for combined cycles. Fabric filters can probably be used for all entrained-bed and fluid-bed gasifiers that do not produce tars. Fabric filters would probably not be applicable to fixed-bed gasifiers due to the need for a quenching operation to condense and remove tars, and the likely presence of droplets or "sticky" particles in the cooled gases. Venturi scrubbers are applicable to all gasification types except the worst-case fluid-bed. If coupled with an upstream cyclone, the venturi would also be applicable to this case.

Since the particulate removal requirements for boiler fuel are not as restrictive as for combined cycles, the number of control devices applicable to boiler fuel gases is increased considerably as compared to combined cycles. Venturi scrubbers are applicable to all gasifier types. Electrostatic precipitators are applicable to the best and average-case fluid-bed and entrained-bed gasifiers. If coupled with an upstream cyclone, ESP's would be applicable to all fluid and entrained-bed gasifier cases. Due to the high carbon content and low resistivity of particulates from fixed-bed gasifiers, ESP's are not applicable to the case of fixed-bed gasifiers. Results for the other types of control devices under consideration are also presented in Table 23.

Sufficient data to serve as a basis for applicability assessments were not available for several relatively advanced control devices still in the developmental stage. The need for additional data for these control devices is discussed in Section 2.2.

Data on the fate of the particulates and tars emitted in the product gases, in terms of their ultimate presence and concentrations in solid, liquid, and gaseous discharge streams, are very preliminary and limited for all gasifier types. The conclusions presented below should, therefore, be considered tentative until confirmed by additional data. The distribution of these particulates and tars in the various discharge streams is dictated by both the removal technology and the physical and chemical characteristics of the contaminants.

In the case of fixed-bed gasifiers, the quench liquor employed to condense and remove the tars contains high concentrations of phenolic compounds. These compounds, together with ammonia and dissolved acid gases, must be removed from the quench liquor. As much water as possible should be recycled to minimize the discharge of liquid effluents. Mercury tends to concentrate in the tar, while most other volatile elements tend to become concentrated on the particulates. Selenium concentrations in the quench liquor are very high.

In the case of fluid-bed gasifiers, most of the available data on the fates of the various contaminants were obtained with the Synthane unit, which also produces tars. Since most other fluid bed gasifiers do not produce tars, these data may not be representative of this generic gasifier type. The available data indicate that many of the trace elements tend to concentrate in the particulates and char. Some of the more volatile elements such as As, Pb, and Hg are also found in potentially harmful concentrations in the tar.

In the case of entrained-bed gasifiers, organics tend to concentrate on the particulate matter, as opposed to scrubber water. Volatile elements such as Hg, Se, and As are not absorbed in the scrubber water. Tars are not produced by entrained-bed gasifiers and, therefore, do not present a disposal problem.

2.2 DATA GAPS AND R & D REQUIREMENTS

As discussed below, the data required for these analyses were, in many cases, quite limited. Thus, the results and conclusions summarized in Section 2.1 and presented in detail in Section 5 should generally be considered as preliminary and tentative until additional, more complete data become available. The deficiencies in the available data base and the associated R & D requirements are discussed below.

2.2.1 Characterization of Particulate and Tar Emissions

The greatest deficiency in the data base employed for the applicability assessments presented in Section 5 was generally found to involve the characterization of the particulate and tar emissions from the various types of gasifiers under consideration. As discussed in Section 2.1, the emission characteristics were, therefore, presented in terms of best-case, worst-case and average (or typical)-case conditions. The conditions under which most of the reported data were obtained are usually unspecified. In addition, the precise influence of many operating conditions (e.g., coal feed rate, steam/coal ratio, steam/air (O_2) ratio, pressure, temperature, etc.) on the emission characteristics is unknown. Thus, more complete data are required for all gasifier types to develop "typical" emission characteristics with a greater degree of accuracy.

The particulate removal efficiency of most control devices is especially sensitive to the particle size distribution. Such data were generally found to be very scarce and incomplete. More complete data over a broad, specified range of gasifier operating conditions are needed. In the case of fluid and entrained-bed gasifiers, particle size data were not available below approximately 35 and 20 micrometers, respectively. Extrapolation of the existing data for large size particles down to the small size particle range was, therefore, required for these two types of gasifiers. Since the concentrations of the smaller size particles in the product gases are of particular interest, due to the fact that the larger particles are easily removed while the particles below approximately 5 micrometers are much more difficult to remove, future R & D programs should concentrate on the collection of particle size data down to the sub-micron size range.

Particle size distribution measurements are usually based on either aerodynamic or optical properties of the particles. Measurements in the same gas stream by these two different techniques often yield inconsistent results. Particle sizes are especially difficult to measure at high temperature and pressure (HTHP) conditions. The collection of reliable particle size distribution data for coal-gasifier product gases will require the development of improved methods and instrumentation suitable for HTHP conditions.

Additional data are also needed to accurately estimate particulate and tar loadings from the various types of gasifiers, particle and tar compositions, and other pertinent properties such as particle resistivity. It should be noted that complete data sets were not available for any of the gasifier types. For example, the particle size distribution might be available for a specific type of gasifier at a given or unspecified set of conditions, whereas particulate loadings and compositions might be available for another type of gasifier within the same generic class, but at a different set of conditions. There is, then, a need for R & D programs to provide complete data for all of the above parameters at the same, specified gasifier operating conditions.

2.2.2 Performance Characteristics of Control Devices

The performance characteristics of the commercial types of control devices are generally well known and documented. There are deficiencies in the data base for several of the more advanced and recently developed types of control devices, which are described in Section 4. The adequacy of the available data for the various types of control devices under consideration in this study are discussed below.

Adequate data are available to describe the particle collection efficiency as a function of size (i.e., particle diameter) for conventional cyclones, venturi and other commercial wet scrubbers, electrostatic precipitators (ESP's) operating at low to moderate temperatures, and conventional baghouse filters.

The vendor-supplied collection efficiency data presented in Section 4.1.3 for the Aerodyne rotary flow cyclone are very encouraging. Additional data are required to confirm these results, however, since tests by Westinghouse Corporation showed significantly lower collection efficiencies. Since data obtained at high temperatures are very limited, additional data are especially needed at these conditions.

The availability of data for several advanced types of wet scrubbers under development to improve the collection of fine, sub-micron particles is very limited. These newer types of scrubbers include foam, steam-assisted, and electrically augmented devices, which are discussed in Section 4.2.8. In addition to the need for more collection efficiency data, more performance testing is needed to assess their operational reliability.

Electrostatic precipitators have undergone only limited testing at high temperatures (up to nearly 1100°C) and pressures (up to 52 MPa). While these limited data are encouraging, more data are required to determine the collection efficiencies and operational reliability under these conditions. Since ESP's have been thoroughly tested at less severe conditions and established as a commercial technology for decades, additional testing at HTHP conditions should be a high priority R & D item.

Conventional baghouse filters are limited to operation at temperatures below 300°C. Ceramic fabrics are being developed to extend the range of possible operating temperatures. The availability of data on ceramic fabric filters is very limited, with most of the data being collected at ambient conditions. More data are, therefore, needed to determine the collection efficiency and operability of ceramic fabric filters.

Porous ceramic filters appear to be very promising for highly efficient collection of particles down to the sub-micron size range at high temperatures. While preliminary data at high temperatures are encouraging, additional testing with larger-scale control devices are required for confirmation. This type of filter should, then, be given serious consideration as a high priority R & D item.

Granular bed filters (GBF) generally appear to be promising for HTHP operation. Most GBF systems are still in the development stage. The GBF developed by Combustion Power Company is the most advanced of this generic class of control device. It is commercially available for operation below 430°C and at ambient pressures. No data are available at HTHP conditions. More data are needed for the Combustion Power Company and other GBF systems to define their collection efficiencies and operational reliability.

In addition to the control devices discussed above, several novel devices are in the early stages of development, with only very limited preliminary data being available. Such devices, discussed in Section 4.6, include the A.P.T. dry scrubber, molten salt scrubber, electrofluidized bed, and the Apitron charged filter. The latter appears to have especially high collection efficiencies down to sub-micron size particles, but operation is restricted to the same temperature limits as a conventional baghouse filter.

2.2.3 End-Use Requirements

The applicability assessments involving the combustion of product gases in gas turbines are very sensitive to the assumed limitation on the particulate concentration in the combusted gases. More data are required to accurately determine the tolerance of gas turbines to particulates.

2.2.4 Fate of Pollutants

In all cases, data on the fates of the particulates and tars, with respect to their presence and concentrations in solid, liquid, and gaseous discharge streams are very preliminary and limited. Data for entrained-bed gasifiers are especially sparse. As previously discussed, most of the data for fluid-bed gasifiers were obtained on the Synthane unit, which produces tars and is, therefore, not representative of most other fluid-bed gasifiers. Thus, additional data are especially needed for more representative fluid-bed gasifiers.

Additional sampling is required to identify and determine the concentrations of contaminants in quench water, solid wastes, tars and scrubber water under better defined conditions. Laboratory analyses should include trace metals and identification of the chemical forms in which they appear, as well as other inorganic and organic compounds. Studies to determine the leachability of trace elements from captured particulates and tars into quench and scrubber water, as well as to ground water after ultimate disposal, would be very useful. Volatility studies are also needed to determine gaseous emissions that would result from liquid and solid discharge streams.

SECTION 3

CHARACTERISTICS OF PARTICULATE AND TAR EMISSIONS

As an initial step in the evaluation of technologies for the control of particulates and tars in gaseous streams originating from coal gasifiers, emissions and process data were obtained for a wide variety of gasifiers. These data, gathered from an array of sources, both published and unpublished, were used to develop "typical" product-gas characteristics for each of the three principal generic classifications of gasifiers (i.e., fixed-bed, fluid-bed, and entrained-bed). Although the availability of pertinent data was found to be quite limited, sufficient data were obtained for this study to permit reasonable characterizations of the particulate and tar emissions from these generic types of gasifiers.

3.1 FIXED-BED GASIFIERS

In fixed (gravitating) bed gasifiers, sized coal is typically fed from above into the gasifier. The fuel bed, which rests on a grate, is maintained at a constant depth (typically 50 cm). Steam and air or oxygen travel countercurrently upward and through the bed. The fuel bed consists of several distinct regions or zones. In the upper or preheat zone, the rising hot gases both dry and devolatize the coal. Below, in the adjacent endothermic gasification or reduction zone, the water-gas reaction occurs. The oxidation or combustion zone at the bottom provides the necessary heat for gasification. In the oxidation zone, the residual material is discharged as ash or slag. Fixed bed-gasifiers have several advantages over the other generic types. The heat economy of the fixed-bed gasifier is generally excellent, mainly because of the countercurrent flow of the gas and coal. Due to the lengthy duration of the coal's residence time, the combustible solids content in the ash residue is minimized. Other advantages include simplicity of operation and the advanced state-of-the-art of fixed-bed gasifiers.

A major drawback to fixed-bed gasifiers is their difficulty in processing caking coals. In addition, tars and oils tend to form in the upper preheat zone of the fuel bed, which can cause plugging of the beds. The tars and oils also result in increased gas cleanup requirements, and associated wastewater treatment and tar/oil separation operations. Another disadvantage is that the coal must be sized to maximize output, and to minimize fines that can plug the bed.

Table 1 lists a number of fixed-bed gasifiers. Typical process parameters and raw gas characteristics for each of these processes are presented in Table 2. Data were gathered from a variety of references, as noted in the table. Characteristics include particle loading, particulate composition, and tar load

TABLE 1 STATUS OF U.S. AND FOREIGN LOW-AND MEDIUM-BTU FIXED-BED GASIFICATION SYSTEMS(1)

Gasifer	Licensor/developer	Number of Gasifiers Built			Location	Scale
		LBG[a]	MBG[b]	SNG[c]		
Lurgi	Lurgi Mineralotechnik GmbH	5	39	22	Foreign	Commercial
Wellman Galusha	McDowell Wellman Engineering Co.	150	-	-	US/Foreign	Commercial
Woodall-Duckham/ Gas Integrale	Woodall-Duckham (USA) Ltd.	72	-	8	Foreign	Commercial
Chapman (Wilputte)	Willputte Corporation	12	-	-	US	Commercial
Riley Morgan	Riley Stoker Corporation	1	-	-	US	Commercial
Pressurized Wellman Galusha (MERC)	ERDA	1[d]	-	-	US	Demonstration
GFERC Slagging	ERDA	-	1[d]	-	US	Demonstration

[a] Low-Btu Gas

[b] Medium-Btu Gas

[c] Synthesis Gas

[d] Under Construction

TABLE 2

OPERATING AND RAW GAS STREAM CHARACTERISTICS
FIXED BED GASIFIERS

	Coal Type	Temperature °C (°F)	Pressure MPa(psia)	Particulate Loading g/nm³(gr/scf)	Particulate Composition	Tar Loading g/nm³ (gr/scf)	Tar Composition	HHV-O_2Blown J/m³ (Btu/scf)	HHV-AirBlown J/m³ (Btu/scf)
Wellman Galusha(2,3)	anthracite bituminous coke	430-820 (800-1500)	0.10 (15)			10-50 (4-21)		$1.1x10^7$ (282)	$5.4x10^6$-$6.3x10^6$ (146-168)
Lurgi(2,3,4,5)	"various coal types"	370-590 (700-1100)	2.07-3.21 (300-465)	0.5-6.0 (0.2-2.5)	C-75-80% ash-10-25%	tar-13 tar oil 79 (33)	tar S-0.77% tar oil S-0.29%	$1.2x10^7$ (307)	$7.2x10^6$ (195)
Woodall Duckham(2,3)	lignite bituminous	120-650 (250-1200)	0.10 (15)			oil and tar 10.3(25)		$1.0x10^7$ (280)	$6.9x10^6$ (185)
Wilputte Chapman(2,3)	all coal types	540-650 (1000-1200)	0.10 (15)						$6.3x10^6$ (170)
Riley Morgan(2)	anthracite bituminous coking bit. bituminous	570-620 (1050-1150)	0.10 (15)	2-4 0.8-1.7		tar 10-20 (4-8) tar oil 10-20 (4-8)		$9.9x10^6$ 266	$4.8x10^6$ - $5.7x10^6$ (130-153)
HERC(2,3,4,5,6)	all coal types	480-650 (900-1200)	0.10-2.10 (15-300)	0.5-6.0 (0.2-2.5)	C-75-80% ash-10-25%	10 (4)	C-82.1 H-7.6 N+O-8.8		$5.2x10^6$ (140)
GFERC(2,4)	lignite lignite char bit. char	85-370 (185-700)	0.66-2.86 (95-415)			tar-10 tar oil-25 (10)		$1.3x10^7$ 350	

and composition. In cases where data differs from one reference to another, a range is provided.

The following operating parameters are expected to influence the composition and/or concentration of impurities in the raw product gas from fixed-bed gasifiers:

- Coal Analysis
- Ash Analysis
- Coal Particle Size Distribution
- Coal Feed Rate
- Steam/Coal Ratio
- Steam/Air (O_2) Ratio
- Recycle Composition and Rate
- Method of Coal Feed
- Number, Design, and Location of Injectors
- Bed Pressure
- Bed Temperature and Temperature Distribution
- Rotational Speed and/or Vertical Travel of Stirrer

Unfortunately, the conditions under which the reported data were collected are usually not specified. In addition, the precise influence of the above parameters on the gasifier emission characteristics is unknown. For the purposes of this study, however, the data obtained for the various types of gasifiers and presented herein can be assumed to be "typical" or "representative" of the particular technologies under consideration. Lurgi and MERC have the most complete data available. These two processes are discussed below.

3.1.1 The Lurgi Process

The Lurgi process, developed by Lurgi Mineralotecnik GmbH of West Germany, is a proven high pressure coal gasification process. The gasifier is a vertical, cylindrical steel pressure vessel that operates at 2.16-3.3 M Pa (300-465 psig). Boiler feed water that is circulated through a water jacket surrounding the gasifier shell recovers heat, improving the overall efficiency of the process. A coal lock hopper above the gasifier feeds crushed and screened coal to the coal bed.

Steam and air, or oxygen, are distributed into the coal bed through the rotating grate. The continuously rotating grate supports the coal bed, assuring a constant and even withdrawal of ash. The ash drops into an ash lock hopper, an integral part of the gasifier.

A typical composition of raw product gases from a Lurgi gasifier is shown in Table 3. Particulate size distribution data is limited. It has been estimated that 40-80% of the particulate matter is smaller than 100 microns. In addition to the particulates and tars in the raw product gases, other potential sources of particulates include the coal and ash lock gases. The composition of the coal lock gas is determined by the method of pressurizing the coal lock. In addition to the components in the raw gas and the lock filling gas

TABLE 3 COMPOSITION OF LURGI RAW PRODUCT GAS (2)

	Coal Type		
Component	Subbituminous A	High Volatile C Bituminous	Subbituminous C
CO	15.1	17.3	17.4
H_2	41.1	39.1	23.3
CH_4	11.2	9.4	5.1
C_2H_4	0.5	0.7	0.63
C_2H_6			
CO_2	30.4	31.2	14.8
N_2 + Ar	1.2	1.2	38.5
O_2	ND	ND	ND
H_2S	0.5	1.1	0.23
COS + CS_2 (kg/kg coal)	(9.2×10^{-4})	(5.4×10^{-4})	PR
Mercaptans	PR	PR	PR
Thiophenes	PR	PR	PR
SO_2	PR	PR	PR
H_2O	PR	PR	PR
Naphthas (kg/kg coal)	(8.6×10^{-3})	(1.0×10^{-2})	(1.6×10^{-2})
Tar (kg/kg coal)	(3.0×10^{-2})	(3.8×10^{-2})	PR
Tar Oil (kg/kg coal)	(3.2×10^{-2})	(3.5×10^{-3})	PR
Crude Phenols	PR	PR	PR
NH_3 (kg/kg coal)	(2.0×10^{-6})	(4.0×10^{-6})	PR
HCN (kg/kg coal)	(6.0×10^{-6})	(6.2×10^{-5})	PR
Particulates (coal fines, ash) (kg/kg coal)	(3.7×10^{-2})	(5.6×10^{-3})	PR
Trace elements	PR	PR	PR
HHV (dry basis):	1.14×10^7 J/Nm^3 (307 Btu/scf)	1.11×10^7 J/Nm^3 (298 Btu/scf)	7.28×10^6 J/Nm^3 (195 Btu/scf)
Gasification media:	Steam/oxygen	Steam/oxygen	Steam/air

ND = presence of component not determined

PR = component is probaby present, amount not determined

All components are presented as % volume, unless otherwise indicated. Component volume % is given on a relative basis to all other components that have a value for volume % listed.

(either cooled raw gas or vent gas from acid gas removal), the coal lock gas may contain entrained coal fines. Particulate emissions have been estimated at 52 g/hr (0.116 lb/hr). The ash lock gas composition is also determined by the method of pressurizing the lock. Steam may be added to the ash lock to pressurize the system. The ash in the hopper may be cooled with a water spray or quenched. This contacting of water and the hot ash produces steam and ash dust. Uncleaned char can react with the steam and any organic compounds in the quench water can be thermally quenched. These reactions contribute to the composition of the gas stream emitted when the ash lock is depressurized. In any case, gases from the gasifier can flow into the lock as it fills with ash. Particulate emissions from the ash lock exhaust fans with cyclone were estimated to be 91 g/hr (0.2 lb/hr).

3.1.2 MERC Process

The MERC stirred-bed reactor has been demonstrated in a 20 TPD pilot plant operated by the Department of Energy at the Morgantown Energy Research Center. Under development since 1958, this gasifier is basically a Wellman-Galusha unit modified for pressurized operation.

Sized coal (50 percent less than 1.25 cm) is transported to the coal feed hopper. Inert gas is used to pressurize the hopper to a pressure slightly greater than the gasifier operating pressure. The coal collects on the grate, forming a bed. The gasifier is a cylindrical, vertical steel pressure vessel with a stirrer in the center and a rotating grate on the bottom. Air mixed with superheated steam is fed into the gasifier beneath the grate. The gases flow upward through the descending coal. The rotating stirrer, which also moves up and down, prevents the coal from caking. The raw product gas exits through the side outlet near the top of the gasifier.

A typical composition of the raw product gas from the MERC gasifier is shown in Table 4. Data on the size distribution of particulates in the raw product gas from the MERC gasifier are presented in Figure 1. Due to the large differences in the size distributions for the different data sets, the available data were classified as worst-case and best-case for the purposes of this study. Worst-case data indicate a relatively high concentration of small particles, which are difficult to remove from the gas stream, whereas best-case indicates a relatively low concentration of small particles. In both cases, the size distribution approximates a log normal function at the smaller particle sizes. The Lurgi data in Table 2 are also presented for comparative purposes.

3.2 FLUIDIZED-BED GASIFIERS

In a fluidized-bed gasifier, crushed coal is fluidized by the gas, passing up through the bed. Because of the intimate solids-gas mixing in the gasifier, the temperature is uniform throughout the bed, resulting in an exit temperature roughly equal to that of the bed.

Since fluid-bed gasifiers have higher particulate loadings in the raw product gas than is typical of fixed-bed processes, more extensive solids removal is required. In contrast, however, tar production is minimal, and the heat content of the product gas is lower, due to the smaller yield of hydrocarbons. Fluid-bed gasifiers have the advantage of being able to utilize a variety of coal types. The

TABLE 4 COMPOSITION OF MERC RAW PRODUCT GAS (2)

Component	Coal Type: Subbituminous A	Coal Type: High Volatile bituminous
CO	16.0	21.6
H_2	19.0	18.7
CH_4	3.5	2.9
C_2H_4	0.3	0.2
C_2H_6		
CO_2	12.6	7.3
N_2 + Ar	48.4	48.9
O_2	ND	ND
H_2S	0.2	0.4
COS + CS_2	PR	PR
Mercaptans	ND	ND
Thiophenes	ND	ND
SO_2	ND	ND
H_2O (kg/kg coal)	(0.64)	(0.37)
Naphthas	PR	PR
Tar (kg/kg coal)	(.034)	(0.20)
Tar Oil	PR	PR
Crude Phenols	PR	PR
NH_3	PR	PR
HCN	ND	ND
Particulates (coal fines, ash) (kg/kg coal)	(0.17)	(3.5×10^{-3})
Trace elements	PR	PR
HHV (dry basis): Joule/Nm^3 (Btu/scf)	5.6×10^6 (150)	6.1×10^6 (164)
Gasification media:	Steam air	Steam/air

ND = presence of component not determined.

PR = component is probably present, amount not determined.

All components are presented as % by volume, unless otherwise indicated. Component volume % is given on a relative basis to all other components that have a value for volume % listed.

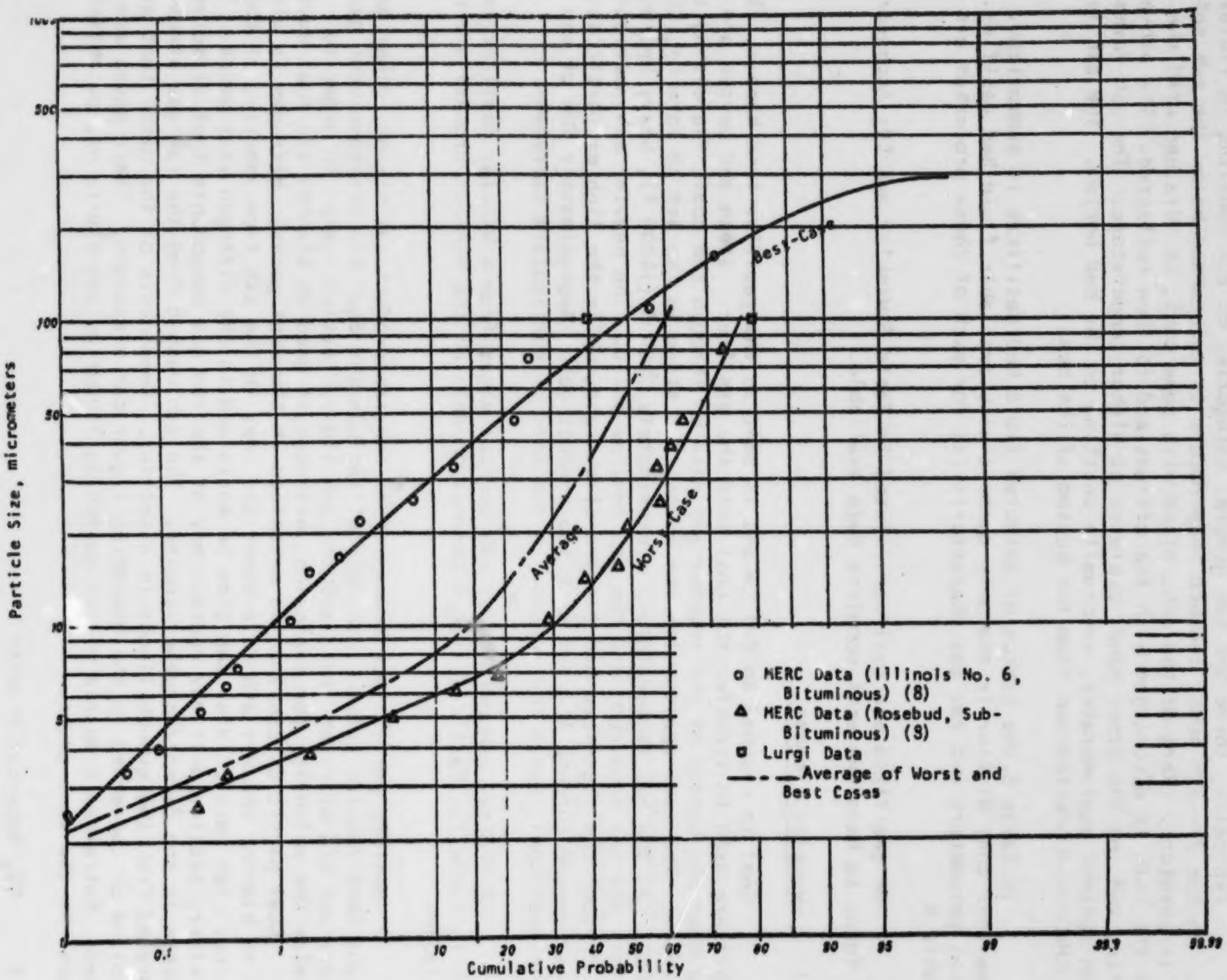

FIGURE 1. Particle Size Distribution for Fixed Bed Gasifiers

gasifiers can be operated at a range of output rates with little loss in efficiency.

Typically, there are two general categories of ash handling in fluidized beds. In the dry-ash mode, the bed temperature is maintained below the ash softening temperature. Part of the ash, mixed with some coal, is "drained off" the bed while the bulk is discharged with the off-gas and is then collected. The ash-aglommerating bed, on the other hand, operates at higher temperature. The ash forms low carbon-content agglomerates, eventually settling to the bed bottom. The ash is then continuously withdrawn from the bottom of the bed.

In Table 5, the status of selected fluid bed gasifiers is summarized. It can be seen that Winkler is the only commercially available fluid-bed gasifier. Typical parameters and raw gas characteristics for each of these processes are shown in Table 6.

Of the fluid bed gasifiers listed in Table 6, Winkler and CO_2 Acceptor were found to have the most complete data available.

3.2.1 Winkler Process

Coal is crushed to 0-1 cm and is sent to the gasifier feed hopper. Screw feeders are used to transfer the coal into the gasifier. Steam and oxygen are added near the bottom of the reactor and pass up through the coal, fluidizing the particles. The coal reacts with the oxygen and steam in the bed to form H_2, CO, CO_2 and CH_4. At the bed temperatures, approximately 760° C (1400° F), heavy hydrocarbons and tars are not produced, and the ash remains solid. The heavier ash particulates drop through the fluidized bed and are discharged, while the lighter particles are carried upward through the bed with the product gas. Approximately 70% of the ash in the feed coal leaves the reactor in the form of particulate carryover.

A typical composition of raw product gases from a Winkler gasifier is shown in Table 7. Particle size distribution data on the Winkler Process are not available.

Besides particulate removal from the raw product gas stream, other gas streams that require particulate control include the coal bin nitrogen vent gases, the dry ash bin nitrogen vent, and the ash slurry settler vent. In order to minimize the potential for explosion, nitrogen is used to blanket the coal dust feed bins. Coal particles can then be entrained in the vent gases. Nitrogen is also used to blanket the dry ash to prevent the char in the ash from reacting or combusting. Ash particulates can then be entrained in the nitrogen vent gases. The ash slurry settler unit may contact any of the raw gas components that dissolve or condense in the direct/scrubber/cooler. The ash washed from the raw gas stream is separated from the quench liquor in a settler. Components of the gases that are dissolved or condensed in the quenching liquor can evaporate. These gases are then vented. Entrained droplets of gas quenching liquor or ash slurry may potentially be present in the vent gases.

3.2.2 CO_2 Acceptor Process

The CO_2 Acceptor Process developed by CONOCO Coal Development Company,

TABLE 5 STATUS OF U.S. AND FOREIGN LOW-AND MEDIUM-BTU FLUID BED GASIFICATION SYSTEMS (1)

		Number of Gasifiers Built				
Gasifier	Licensor/developer	LBG[a]	MBG[b]	SNG[c]	Location	Scale
Winkler	Davy Powergas	-	23	14	Foreign	Commercial
BCR Low-Btu	Bituminous Coal Research, Inc.	1	-	-	US	Demonstration
Hygas	Institute of Gas Technology	-	1	-	US	Demonstration (High-Btu)
Synthane	ERDA	-	1	-	US	Demonstration (High-Btu)
CO_2 Acceptor	ERDA	-	1	-	US	Demonstration (High-Btu)
U-Gas	Institute of Gas Technology Phillips Petroleum Corp.	1	-	-	US	Pilot
Battelle/Carbide	Battelle Memorial Institute	-	1	-	US	PDU
COGAS	COGAS Development Company	-	1	-	US	PDU
Westinghouse	Westinghouse Electric Co.	1	-	-	US	PDU

[a] Low Btu Gas

[b] Medium-Btu Gas

[c] Synthesis Gas

TABLE 6

OPERATING AND RAW GAS STREAM CHARACTERISTICS
FLUID BED GASIFIERS

	Coal Type	Temperature ^{o}C (^{o}F)	Pressure MPa(psia)	Particulate Loading g/nm^3(gr/scf)	Particulate Composition	Tar Loading g/nm^3 (gr/scf)	Tar Composition	HHV-O$_2$Blown J/m^3 (Btu/scf)	HHV-Air Blown J/m^3 (Btu/scf)
Winkler(2,3,4)	several coal types	590-730 (1100-1450)	0.10 (15)		C-30% ash-70%	None		1.1×10^7 (288)	4.7×10^6 (126)
Synthane(3,4,5)	all types	760 (1400)	6.90 (1000)	4.8-12 (2-5)	C-80% ash-20%	2.4-17 (1-7)		1.3×10^7 (355)	6.1×10^6 (165)
CO$_2$ Acceptor (3,4,5)	lignite sub-bituminous	815 (1550)	1.03-2.06 (150-300)	26 (10)	C-8% ash-88%	None		1.4×10^7 (380)	
Hygas(3,4)	all coals	1100 (2000)	6.90-10.3 (1000-1500)	120 (50)	C-55% ash-40% O$_2$-5%	None		1.3×10^7 (375)	
CoGas(3)	all types	870 (1600)	0.21-0.41 (30-60)						
Hydrane(3)	all types	540-815 (1000-1500)	6.90 (1000)			4.3 (1.8)		2.9×10^7 (784)	
Union Carbide(3)		870-980 (1600-1800)	0.69 (100)	0.0-1.2 (0.05-0.5)		None		1.2×10^7 (330)	
Westinghouse(3)	"variety of coals"		0.90-1.38 (130-200)	8 (3.3)		None			5.0×10^6 (135)
U-Gas(3)	non-caking caking req. pretreatmt.	840-1040 (1550-1900)	0.34-2.41 (50-350)			None			5.7×10^6 (154)
BCR (3)			$\leq$1.62 ($\leq$235)			None			6.0×10^6 (160)
Ignifluid(5)		590-715 (1100-1320)	0.10-0.50 (15-75)	84 (35)					(125)

TABLE 7 COMPOSITION OF WINKLER RAW PRODUCT GAS (2)

	Coal Type		
Component	Subbituminous A	Lignite	Subbituminous
CO	22.0	35.5	37.0
H_2	14.0	40.0	37.0
CH_4	1.0	2.8	3.0
C_2H_4	ND	ND	ND
C_2H_6	ND	ND	ND
CO_2	7.0	19.9	20.0
N_2 + Ar	56.0	1.8	3.0
O_2	ND	ND	ND
H_2S	PR	PR	PR
COS + CS_2	ND	ND	ND
Mercaptans	ND	ND	ND
Thiophenes	ND	ND	ND
SO_2	ND	ND	ND
H_2O	PR	PR	PR
Naphthas	NP	NP	NP
Tar	NP	NP	NP
Tar Oil	NP	NP	NP
Crude Phenols	ND	ND	ND
NH_3	ND	ND	ND
HCN	ND	ND	ND
Particulates (coal fines, ash)	PR	0.46 kg/kg coal DAF	PR
Trace Elements	PR	PR	PR
HHV (Dry Basis): J/Nm^3 (Btu/scf)	4.66×10^6 (125)	1.01×10^7 (272)	1.0×10^7 (270)
Gasification media:	Steam/air	Steam/O_2	Steam/O_2

ND = presence of component not determined

PR = component is probably present, amount not determined

NP = component is probably not present

All components are presented as % by volume, unless otherwise indicated. Component volume % is given on a relative basis to all other components that have a value for volume % listed.

has undergone testing at 27230 kg/day (30 TPD) at a pilot plant located in Rapid City, S.D. This process consists of two fluidized bed reactors, including the coal gasifier itself and a regenerator for spent limestone or dolomite. Control of particulates and tars will be discussed in this report only for the gasifier, since the regenerator is unique to this process and, therefore, is not representative of other gasification processes.

Lignite or subbituminous coal is crushed to 0.1 to 1 cm and is fed into the bottom of the gasifier. Steam enters through a side nozzle at roughly the same bed height as the coal feed. Above the fluidized bed, hot recirculated acceptor, CaO is fed into the gasifier and falls through the bed. The gasifier fluid bed is a mixture of acceptor and char, with the lighter char concentrated in the upper zones of the gasifier. The following exothermic reactions occur in the main gasifier:

$$CaO + CO_2 \longrightarrow CaCO_3$$
$$CO + H_2O \longrightarrow CO_2 + H_2$$

The heat produced by these reactions and the sensible heat of the acceptor supply the heat necessary to drive the endothermic gasification reactions:

$$C + H_2O \longrightarrow CO + H_2$$
$$2C + H_2O + H_2 \longrightarrow CH_4 + CO$$

The raw product gas then leaves the gasifier through an internal cyclone.

The carbonated acceptor flows out of the reactor and is conveyed to the bottom of the regenerator by air or recycled gas. Residual char is withdrawn through a standleg near the top of the fluidized bed and is transferred to the regenerator. The char is burned at 1010° C (1850° F) with air in the regenerator fluidized bed. The carbonated acceptor is calcined at this temperature to CaO and CO_2, with the CaO then being returned to the gasifier. Particulate matter is removed from the regenerator flue gas by means of a cyclone.

It should be noted that the particulate matter released from the gasifier consists primarily of char and ash, with a negligible amount of acceptor being present. Thus, the emissions characteristics for the gasifier should be typical of other types of fluid-bed gasifiers.

Reported compositions of the raw product gases and the lockhopper vent gases are presented in Table 8. The particle size distribution is shown on Figure 2. The CO_2 Acceptor data in Figure 2 were obtained in an air-blown system using coal with 7.5% ash. The particulates tested consist of the char that escaped the internal cyclone of the gasifier.

In addition to the CO_2 Acceptor data in Figure 2, particle size distribution data are also presented for the Ignifluid process. The Ignifluid gasification system employs a fast fluid bed and temperatures of 1095° C (2000° F) or more, which results in a "sticky" ash that tends to agglomerate. The particle sizes are, therefore, relatively large, as can be seen from Figure 2.

TABLE 8

COMPOSITION OF CO_2 ACCEPTOR RAW PRODUCT AND LOCKHOPPER VENT GASES (11)

	Raw Product Gases	Lockhopper Vent Gas
CH_4	8.9	
CO	12.2	
CO_2	4.8	33.1
H_2	50.8	
N_2	0.1	65.1
NH_4	<0.1	
H_2S	<0.1	
H_2O	21.0	1.3
Inert	1.3	
SO_2		<0.1
O_2		<0.1

All components are presented as percent volume, unless otherwise indicated. Component volume percent is given on a relative basis to all other components that have a value for volume percent listed.

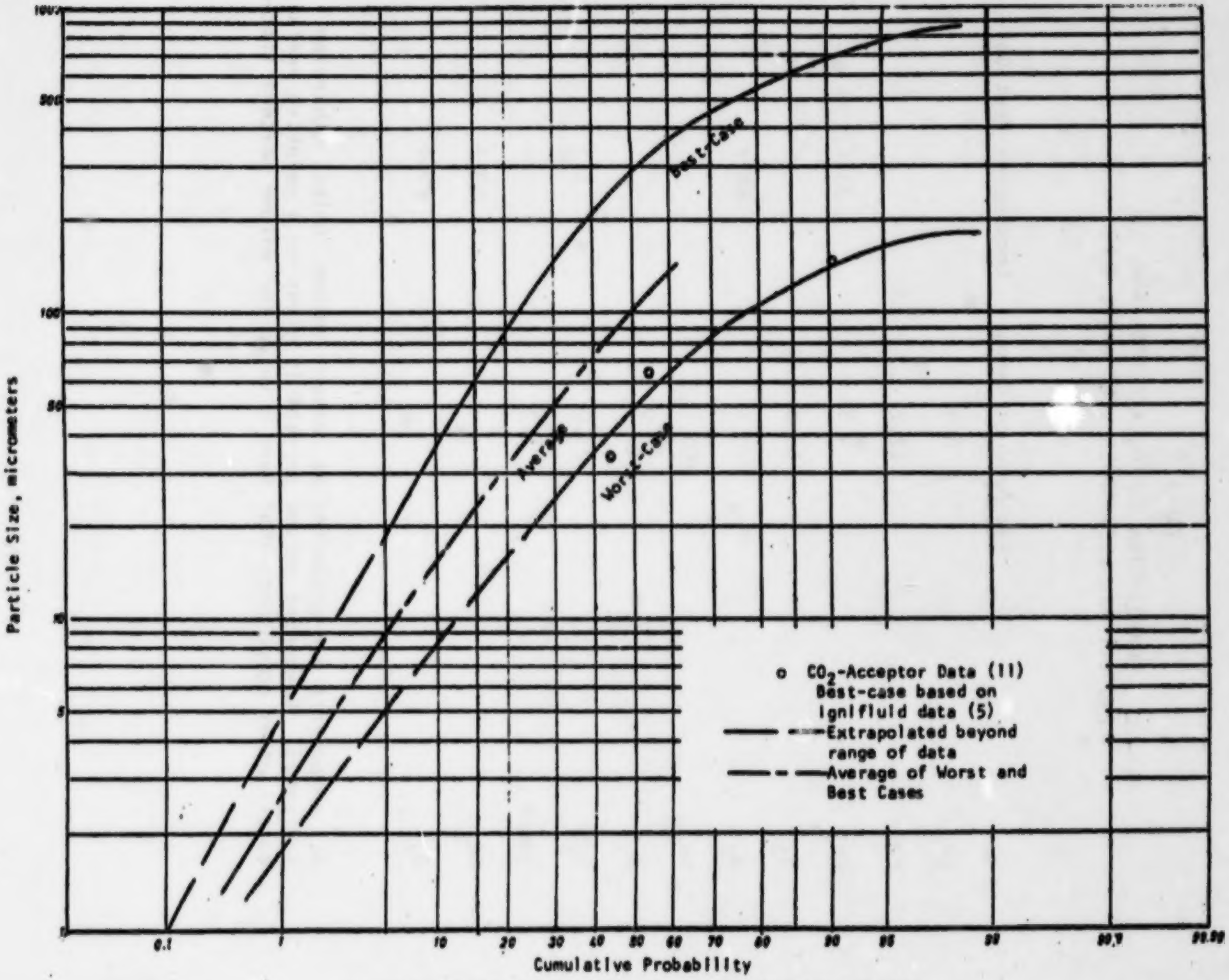

FIGURE 2. Particle Size Distribution for Fluid Bed Gasifiers

3.3 ENTRAINED BED GASIFIERS

In the entrained-bed gasifier, the gases that are fed to the reactor and gases formed during the gasification reactions carry or "entrain" pulverized coal through the gasifier. Because the flow is concurrent, the reaction rate decreases as the coal particles travel through the reactor. Since high temperatures are maintained to minimize the reactor size,no tar or heavy oils are produced.

An advantage of entrained-bed gasifiers is their capability to process all coal types. This is due to relatively large separations between the particles, which minimizes agglomeration. Other advantages of entrained-bed gasifiers include a smaller bed reactor volume per unit of energy production, and the ease of disposal of fused ash in comparison to loose flyash. Disadvantages of entrained-bed gasifiers are primarily due to the low concentration of fuel in the gasifying medium and the concurrent flow. Only 85-90% of the carbon can be economically gasified in a single pass. Due to the high temperatures of the gases leaving the reactor, heat recovery is necessary to reduce energy losses and improve the thermal efficiency. This is complicated by the presence of solids in the stream and the possible deposition of molten ash on heat transfer surfaces.

The status of some of the more promising entrained-bed gasifiers is shown in Table 9. It can be seen that Koppers-Totzek is the only commercially available entrained-bed gasifier. Typical process parameters and raw gas stream characteristics are presented in Table 10.

Of the entrained bed gasifiers listed in Table 10,Koppers Totzek and Bi-Gas were found to have the most complete data available. In addition to the list of parameters in Section 3.1 for fixed-bed gasifiers, the gas velocity and residence time are expected to affect the product gas characteristics from entrained-bed gasifiers. As in the case of both fixed and fluid-bed gasifiers, the many parameters that can affect the product gases are usually unspecified, and the effects of these parameters on the product gas characteristics can generally not be quantified. For the purposes of this study, however, the product gas characteristics presented herein can be assumed to be "typical" or "representative" of other gasifiers within the same generic classification.

3.3.1 Koppers Totzek Process

The Koppers Totzek (K-T) process is a commercially proven low pressure coal gasification process. The gasifier is a horizontal eliptical double walled steel vessel with refractory lining and has either two or four truncated cone-shaped heads mounted on either end of the ellipsoid. The coal, steam and oxygen are injected through burners. A waste heat boiler at the top of the gasifier recovers heat from the hot effluent gases. The carbon and volatile matter are gasified, and between 50-70% (4) of the liquefied coal ash falls into a water quench tank in the form of molten slag. The remainder of the coal ash is present as particulate carry-over in the raw product gas. Table 11 indicates the projected composition of the raw product gas.

Typically, in the K-T process, gas departing the gasifier is quenched by

TABLE 9

STATUS OF U.S. AND FOREIGN LOW-AND MEDIUM-BTU ENTRAINED-BED GASIFICATION SYSTEMS(1)

		Number of Gasifiers Built				
Gasifier	Licensor/developer	LBG[a]	MBG[b]	SNG[c]	Location	Scale
Koppers-Totzek	Koppers Company, Inc.	-	-	39	Foreign	Commercial
Bi-Gas	Bituminous Coal Research, Inc.	-	1	-	US	Demonstration
Texaco	Texaco Development Corporation	-	-	1	US	Demonstration
Combustion Engineering	Combustion Engineering Corporation	1	-	-	US	Demonstration
Babcock & Wilcox	Babcock & Wilcox Corporation	1	-	-	US	Demonstration
Coalex	Inex Resources, Inc.	1	-	-	US	Pilot
Foster Wheeler	Foster Wheeler Energy Corp.	1	-	-	US	Pilot

[a] Low-Btu Gas

[b] Medium -Btu Gas

[c] Synthesis Gas

TABLE 10

OPERATING AND RAW PRODUCT GAS STREAM CHARACTERISTICS
ENTRAINED BED GASIFIERS

	Coal Type	Temperature °C (°F)	Pressure MPa(psia)	Particulate Loading g/nm^3(gr/scf)	Particulate Composition	Tar Loading g/nm^3 (gr/scf)	Tar Composition	HHV-O$_2$Blown J/m^3 (Btu/scf)	HHV-Air Blown J/m^3 (Btu/scf)
Koppers Totzek (2,3,4)	all types	1480 (2700)	0.10 (15)	30-60 (12-25)	C-10% ash-90%	None		1.1x10^7 (290)	
BI-Gas(2,3,)	lignite sub-bit. bitumin.	745-1180 (1375-2160)	1.62-10.3 (235-1500)	230 (96)	char-96-89% ash-12-10% volatiles- 2-1%	None		1.3x10^7 (356)	5.3x10^6 (142)
Texaco (2,3)	lignite bitumin.	200-260 (400-500)	2.10-8.27 (300-1200)			None		9.4x10^6 (253)	6.5x10^6 (175)
Combustion Engineering(3)	all types	870 (1600)	0.10 (15)						4.7x10^6 (127)
B & W(3)	all types	980 (1800)	0.10-2.10 (15-300)			None		1.1x10^7 (30)	3.9x10^6 (102)
Coalex(2)	all types	925-950 (1700-1740)	0.10 (15)						4.9x10^6 (133)
Foster Wheeler(2,3)	non-caking	upper stage 980-1150 (1800-2100) lower stage 1370-1540 (2500-2800)	2.41 (350)			None			6.6x10^6 (177)

TABLE 11 COMPOSITION OF KOPPERS-TOTZEK RAW PRODUCT GAS (2)

Component	Coal Type Lignite A	 B bituminous	 C bituminous
CO	56.87	52.35	52.51
H_2	31.30	35.66	35.96
CH_4	PR	PR	PR
C_2H_4	ND	ND	ND
C_2H_6	ND	ND	ND
CO_2	10.0	10.0	10.0
N_2 + Ar	1.18	1.12	1.15
O_2	ND	ND	ND
H_2S	0.60	0.82	0.36
COS + CS_2	0.05	0.05	0.02
Mercaptans	ND	ND	ND
Thiophenes	ND	ND	ND
SO_2	PR	PR	PR
H_2O	PR	PR	PR
Naphthas	ND	ND	ND
Tar	ND	ND	ND
Tar Oil	ND	ND	ND
Crude Phenols	ND	ND	ND
NH_3	<0.2	<0.2	<0.2
HCN	PR	PR	PR
Particulates (coal fines, ash) (kg/kg DAF coal)	(0.08)	(0.06)	(0.08)
Trace elements	PR	PR	PR
HHV (dry basis): Joule/Nm^3 (Btu/scf)	1.1×10^7 (290)	1.1×10^7 (290)	1.1×10^7 (290)
Gasification Media:	Steam/O_2	Steam/O_2	Steam/O_2

ND = presence of component not determined

PR = component is probably present, amount not determined

All components are presented as % volume, unless otherwise indicated. Component volume % is given on a relative basis to all other components that have a value for volume % listed.

water sprays. This quenching is done to solidify the entrained slag particles to prevent deposition on the downstream boiler tubes. The gas then passes through a waste heat boiler where high pressure steam is produced. After leaving the waste heat boiler, the gas is cleaned by a venturi scrubbing system. The particle size distribution data presented in Figure 3 was collected at a sampling point between the waste heat boiler and the water quenching operation.

3.3.2 Bi-Gas Process

This two-stage entrained flow gasifier developed by Bituminous Coal Research, Inc. (BCR) is currently in the pilot plant stage. A 120 ton/day pilot plant has been constructed in Homer City, Pennsylvania.

Run-of-the-mine coal is crushed, dried, and pulverized to .05 cm (-200 mesh). The coal is combined with hot gas recycled from the gas purification section, and is fed into the upper stage of the gasifier. The coal reacts with gas from the lower stage and steam,and yields the product gas.

Residual char is removed from the gas by cyclones and is recycled with steam and air. The hot gas flows to the upper stage for reaction with the coal. The molten slag collects and drains from the bottom of the lower stage into the slag pot where it is water quenched.

Table 12 presents data on the composition of the raw product gas. Available particle size distribution data are shown in Figure 3.

In addition to the raw product gas, another emission source is the slag lock gas. When the slag lock is depressurized to discharge accumulated slag, a gaseous discharge stream will be emitted that may contain slag particles, any of the raw gas components, plus volatiles found in the slag quench water. Controls, dependant upon the makeup of the stream, may include a cyclone or combustion in a flare or boiler.

3.4 SUMMARY OF DATA

The particulate and tar loading data and the particle size distribution data presented in Sections 3.1 through 3.3 are summarized in Table 13. The best, worst, and average-case data for the particulate and tar loadings from fixed-bed, fluid-bed, and entrained-bed gasifiers were estimated from the detailed data for the individual gasifier types in Tables 2, 6, and 10. It can be seen that fixed-bed gasifiers produce the smallest particulate loadings, while the entrained-bed gasifiers produce the greatest particulate loadings. Only the fixed-bed gasifiers produce a significant amount of tars. The particle size distribution data in Table 13 were obtained from Figures 1, 2 and 3.

It should be noted that the data in Table 13 should not be interpreted as being indicative of any particular type of gasifier, but instead portray characteristics expected of processes in general for the generic categories under consideration. The best and worst-case data for particulate and tar loadings should reasonably reflect the extremes to be expected from each generic class of gasifier. Due

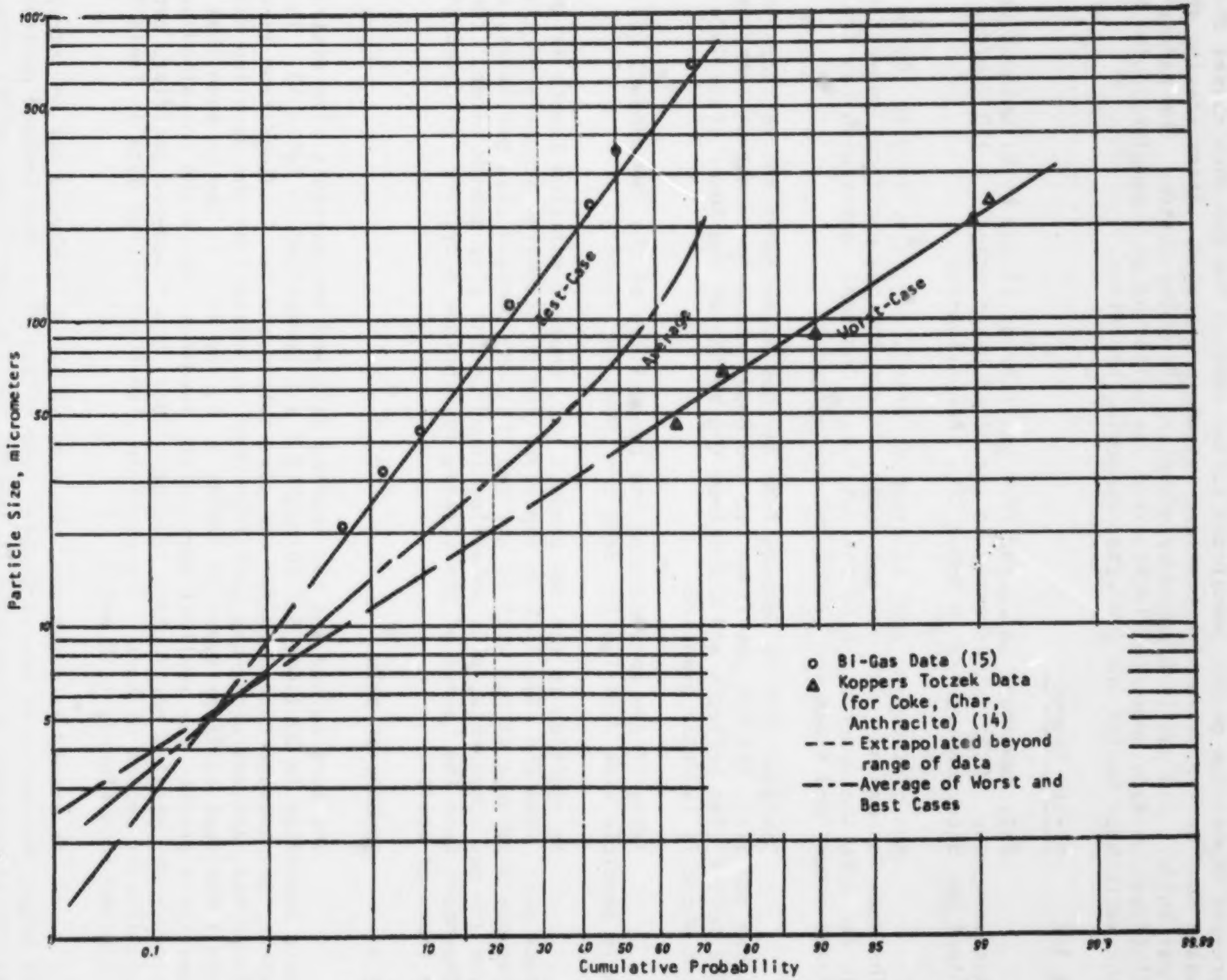

FIGURE 3. Particulate Size Distribution for Entrained Bed Gasifiers

TABLE 12 COMPOSITION OF BI-GAS PRODUCT GAS (2)

Component	Coal Type Western Kentucky #11 Bituminous	 Illinois #6 Bituminous
CO	40.6	18.1
H_2	22.5	13.1
CH_4	14.3	3.6
C_2H_4	ND	ND
C_2H_6	ND	ND
CO_2	12.9	8.3
N_2 + Ar	0.6	45.8
O_2	ND	ND
H_2S	1.3	0.5
COS + CS_2	PR	0.1
Mercaptans	ND	ND
Thiophenes	ND	ND
SO_2	ND	ND
H_2O	7.7	10.2
Naphthas	NP	NP
Tar	NP	NP
Tar Oil	NP	NP
Crude Phenols	ND	ND
NH_3	PR	0.4
HCN	ND	ND
Particulates (coal fines, ash)	PR	PR
Trace elements	PR	PR
HHV (Dry basis):		
J/Nm^3	1.30×10^7	5.29×10^6
(Btu/scf)	(350)	(142)
Gasification Media:	Steam/O_2	Steam/Air

ND = presence of component not determined

PR = component is probably present, amount not determined

NP = component is probably not present

All components are presented as % volume, unless otherwise indicated. Component volume % is given on a relative basis to all other components that have a value for volume % listed.

TABLE 13 SUMMARIZED PARTICULATE AND TAR LOADINGS AND PARTICLE SIZE DISTRIBUTIONS

	Particulate Loading (g/m^3)	Tar Loading (g/m^3)	Percent Particles (by weight) Less Than Specified Diameter (In Micrometers)				
			1	5	10	50	100
Fixed Bed							
Best Case	0.5	10.0	<0.1	0.1	1	23	50
Worst Case	6.0	50.0	<0.1	4.0	30	67	76
Average	3.0	18.0	<0.1	2.0	15	45	63
Fluid Bed							
Best Case	1.2	None	0.1	1.0	2	13	22
Worst Case	120.0	None	0.5	5.0	12	52	78
Average	26.0	None	0.3	3.0	7	33	50
Entrained Bed							
Best Case	30.0	None	<0.1	0.5	2	12	24
Worst Case	230.0	None	<0.1	0.5	4	66	90
Average	110.0	None	<0.1	0.5	3	39	57

to the limited amount of particle size data available for this study, the data in Table 13 were obtained by considering all the available data for each generic class of gasifier, and by employing engineering judgment to estimate values representative of each class.

The data in Table 13 will be utilized as a basis for estimating the particulate and tar loadings on the control technologies described in the next section, and for assessing the adequacy of each control technology for reducing the particulate and tar concentrations to acceptable levels.

SECTION 4

ALTERNATE CONTROL TECHNOLOGIES

Alternate control technologies for removing the particulate and tar emissions from the product gases of the various types of gasifiers discussed in Section 3 are described in this section. Control technologies both commercially available and under development are considered. Detailed descriptions of most of these control devices are readily available in a wide variety of books, reports, and papers in the open literature. Brief summaries of important design and operating features are presented herein, with emphasis on characterizing the particulate removal efficiency of each control device. These performance characteristics are then employed in Section 5 in assessing the applicability of each control device to each type of generic gasifier previously discussed.

4.1 CYCLONES

Cyclones utilize the centrifugal force created by a spinning gas stream to separate particulates from the carrier gas. Spinning motion is imparted to the carrier gas by tangential gas inlet, vanes or a fan. Particulates, which have a greater applied centrifugal force than that of the gas molecules, move outward to the wall and are carried down a receiver. The major classes of cyclones include conventional cyclones, multiclones, and rotary flow cyclones.

Conventional cyclones have the advantage of being a proven technology and a simple device with no moving parts. However, they suffer from the disadvantage of having low removal efficiencies for particulate sizes less than 5 micrometers. Because of their relatively low capital and operating costs, cyclones are commonly used as pre-cleaners to remove most of the large particles in a gas stream upstream of a more expensive control device (e.g., venturi scrubber or electrostatic precipitator) required to remove the smaller size particles. To improve the collection efficiency, multiclones and rotary flow cyclones were developed. Each class of cyclones is discussed below.

4.1.1 Conventional Cyclones

Design procedures for conventional cyclones have been highly developed from theoretical considerations, supplemented to some extent by empirical techniques gained from operating performance data. The particulate removal efficiency has been found to be very dependent on particle size. It is, therefore, necessary to define the particulate size distribution in order to successfully predict the removal efficiency that will be obtained with a particular design for a given set of operating conditions. High efficiency cyclones are generally considered to be those with a body diameter less than 0.23 meters, since the smaller the body diameter, the larger the separation force created.

Particulate collection efficiency increases with an increase in particulate diameter, particulate density, inlet velocity, cyclone body length, ratio of cyclone body diameter to outlet diameter, and the smoothness of the inner wall. Efficiency decreases as the gas viscosity, gas density, body diameter and gas outlet diameter increase. A typical set of data on the efficiency of collection as a function of temperature are shown in Figure 4. Since the gas viscosity is proportional to temperature, an increase in temperature results in a decrease in the efficiency.

A further illustration of the effect of high temperature and pressure on particulate collection is presented in Figure 5. This is done by determining the collection efficiency of a cyclone operating at various temperatures and pressures for the same inlet velocity. Curve 1 in this figure shows a typical efficiency curve for a high efficiency cyclone operating at ambient conditions. The collection efficiency drops significantly as the temperature increases to 1100°C, as shown in Curve 2. Curve 3 shows the collection efficiency decrease, again for small particulates, as the pressure increases from 0.1 M Pa to 1.5 M Pa.

4.1.2 Multiclones

Multiclones are designed to increase the conventional cyclone performance by reducing the diameter of the cyclone while maintaining a constant inlet velocity since the centrifugal force applied to the particulates varies inversely with the diameter of the cyclones. These devices are fabricated by manifolding together banks of smaller cyclones, usually with a common inlet plenum chamber, dust storage bin and outlet plenum chamber. In order to achieve the same level of collection efficiency as a single tube with the same diameter and inlet velocity, it is necessary to equalize the gas loading between the cyclones to prevent backflow, plugging or re-entrainment from the dust bin.

Combustion Power Company has tested two stages of multiclones in their CPU-400 Pilot Plant to remove fly ash and fine bed material particulates (46). Results show that the cyclone tubes of both stages are prone to plugging in the lower cone body due primarily to suspected cross flow between the tubes. The performance of these units is similar to that of small conventional cyclones (47).

Multiclones have been commercialized, as well as being demonstrated at high temperature (788°C) and high pressure (5.0 M Pa). Grade efficiency data reported by Environmental Elements Corporation multiclones are shown in Figure 6.

4.1.3. Rotary Flow Cyclones

Rotary flow cyclones are designed to augment the normal tangential swirl of the inlet gas by the addition of a secondary airflow. By doing so, the possibility of short-circuiting of particulates from inlet to outlet is greatly reduced. Two rotary-flow type cyclones have been developed to improve cyclone collection efficiency, as discussed below.

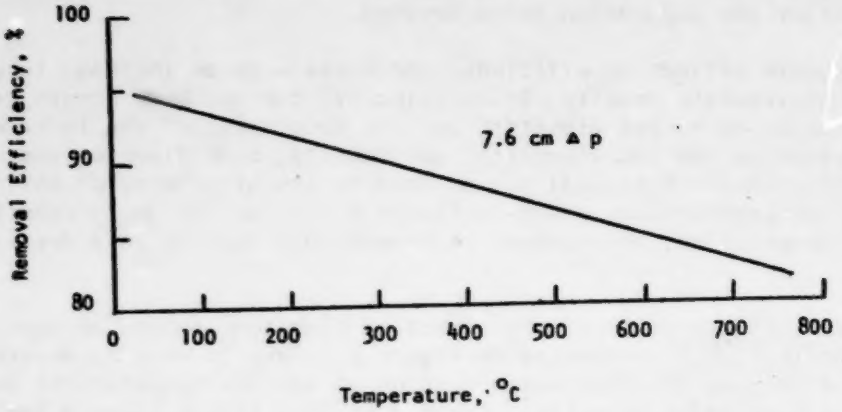

FIGURE 4. Effect of Temperature on Conventional Cyclone Efficiency (44)

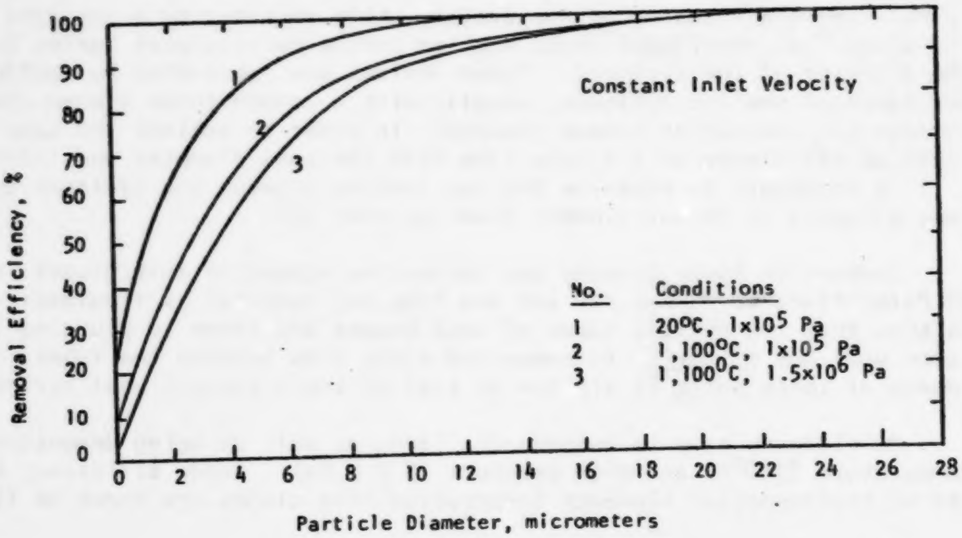

FIGURE 5. The Effects of High Temperature and Pressure on the Collection of A High Efficiency Conventional Cyclone (45)

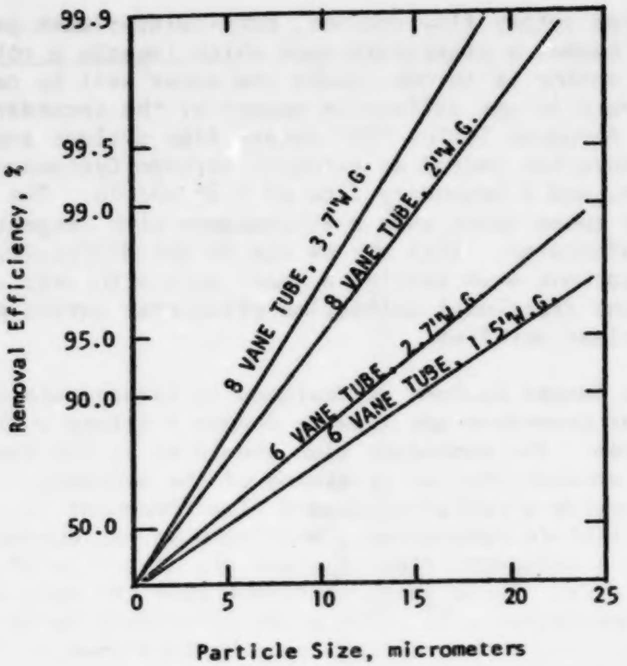

FIGURE 6. Fractional Removal Efficiency Curves of Multiclones by Environmental Element Corp. (48)

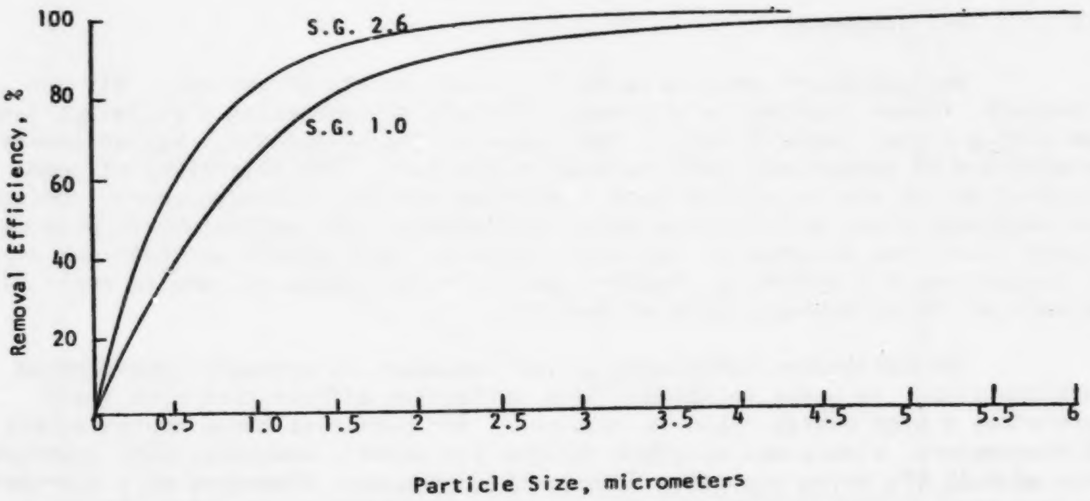

FIGURE 7. Fractional Removal Efficiency Curves for Aerodyne Series "SV" Dust Collector (49)

In the Aerodyne rotary flow cyclone, particulate-laden gas enters the collection chamber and passes a stationary vane which imparts a rotary motion to the flow. Particulate matter is thrown toward the outer wall by centrifugal force, where it is swept downward to the collection hopper by the secondary flow. The vendor curves for the Aerodyne Series "SV" rotary flow cyclone are presented in Figure 7. Westinghouse has tested an Aerodyne Tornado Cyclone with a primary air flow of 1.42 m^3/min, and a secondary flow of 0.84 m^3/min. The grade efficiency data obtained in these tests show a discrepancy with respect to the claimed performance by the manufacturer. This may be due to the difficulty of holding design removal specifications when testing a small unit with less than 11.3 m^3/min capacity (50). Thus, the fractional collection efficiency curves presented in Figure 7 need to be further verified.

The Donaldson Tanjet Cyclone is designed to incorporate a low-volume, high velocity tangential secondary gas flow to induce a strong vortex flow on a primary axial flow stream. The secondary flow should be at the same temperature as the primary flow to prevent thermal stressing of the assembly. The tangential jets are designed to provide a radially outward flow component in the separation zone,which aids in particulate separation. Westinghouse has operated a Tanjet unit at 3.7 m^3/min with a secondary flow of clean air at a rate of 0.4 m^3/min at a pressure drop of 3.3 M Pa. These tests confirmed that the unit maintains its performance at high temperatures (5). The grade efficiency curve is presented in Figure 8. The Tanjet program was discontinued by Donaldson in 1976 to await the development of an attractive market. Further work to improve the collection efficiency and to refine the collection hopper are needed. In addition, the use of clean secondary air, at pressure, must be considered as a significant process cost and should be included in any overall design.

4.2 WET SCRUBBERS

Wet scrubbers are available in a wide variety of designs. All wet scrubbers, though, operate on a common principle of contacting a pollutant-laden gas with a liquid (usually water) that captures the pollutants. Wet scrubbers can be utilized to remove both particulates and/or tars. The objectives of good scrubber design are to provide good liquid-gas contact, minimize energy consumption and equipment size, and minimize water requirement. All wet scrubbers produce a liquid slurry for disposal or further treatment. Most modern applications attempt to concentrate the solids to simplify their ultimate disposal, and to recirculate as much of the scrubbing liquid as possible.

The collection efficiency of wet scrubbers is strongly dependent on particle size. In order to achieve high collection efficiencies with small particles, a high energy input is required. For particles above approximately 10 micrometers, simple wet scrubber designs are usually adequate, with pressure drop of 0.25 kPa being typical. Fine particulates with diameters of 1 micrometer or less require more complex scrubbers with pressure drops usually well above 1.25 k Pa. In exceptional circumstances, pressure drops up to 25 k Pa have been employed.

Wet scrubbers have been found to be very effective in removing tars from raw product gases. Commercially available gasification systems generally

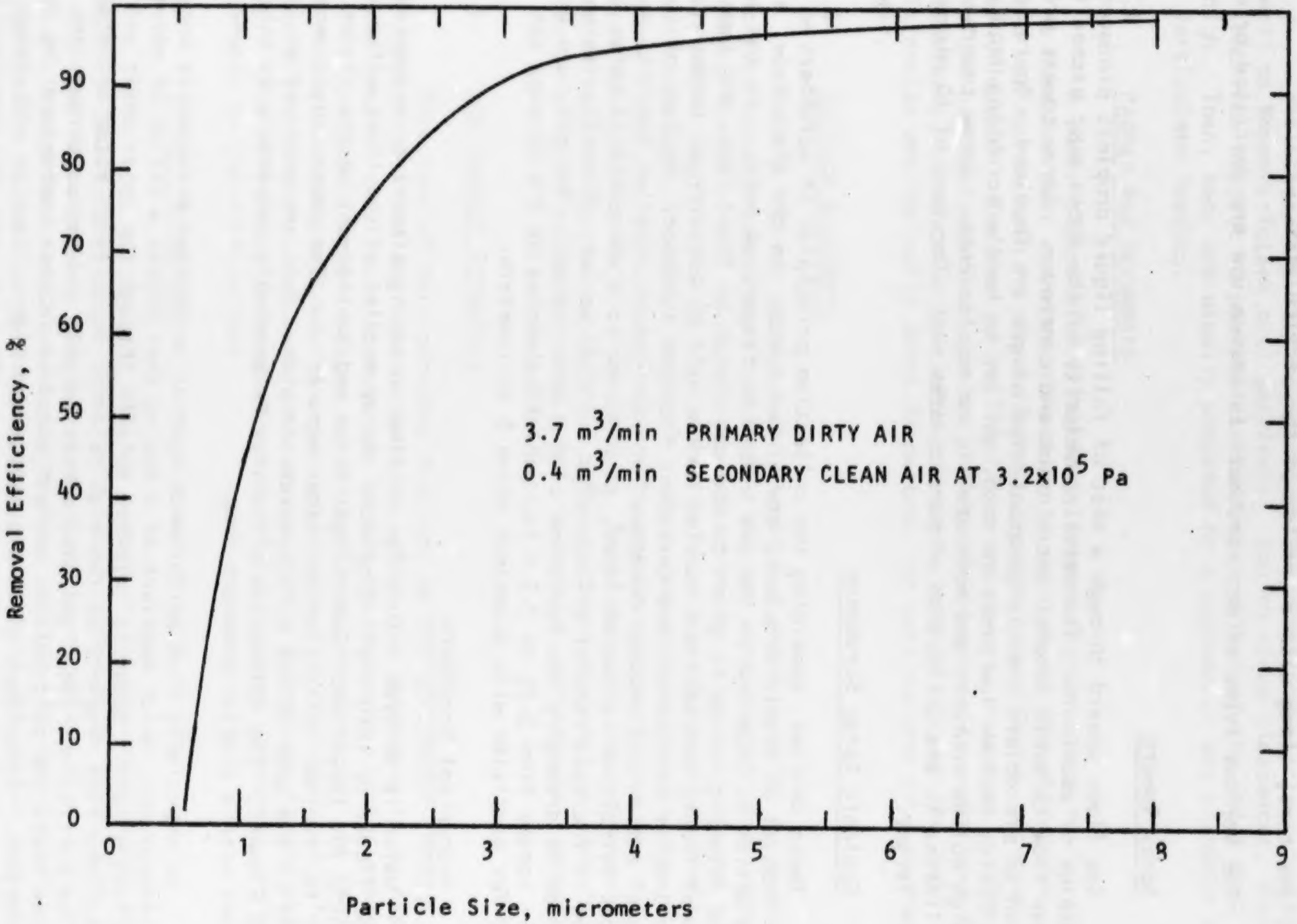

FIGURE 8. Fractional Removal Efficiency Curve for Donaldson Tanjet Cyclone (5)

have employed various types of wet scrubbers to quench and cool the gases and knock out the tars, along with a portion of the particulates.

The various types of wet scrubbers in common use are described briefly below.

4.2.1 Spray Towers

Gas flows upward through a mist of falling liquid droplets produced by spray nozzles or atomizers. The settling velocity of the drops must exceed the upward gas flow to avoid droplet entrainment and carryover. Spray towers are often used as precoolers when large quantities of gas are involved. Operating characteristics include low pressure drop, ability to handle scrubbing liquids with a high solids content, and moderate liquid requirements. Spray towers are usually limited to the collection of particulates with diameters of 10 micrometers or larger.

4.2.2 Cyclonic Spray Scrubbers

These devices, combining the collection principles of scrubbers with the cyclonic removal of liquid droplets, are of two types. In the first type, a spinning motion is imparted to the gas stream by tangential entry. In the second type, the rotating motion is given to the gas stream by fixed vanes and impellers. The sprayed liquid droplets are carried to the wall by centrifugal forces, thereby reducing droplet entrainment and carryover from the scrubber. Because of the centrifugal action and reduced tendency for entrainment, smaller droplets and higher gas velocities can be employed, as compared to a conventional spray chamber, resulting in increased removal efficiencies. A wide variety of configurations can be employed in arranging the locations of the water sprays. The pressure drop typically ranges from 3.75 to 7.5 h Pa, and efficiencies of 90% or more can be obtained for particles with diameters above 5 micrometers.

4.2.3 Mechanical Scrubbers

Water is sprayed into a fan or other rotating element to mechanically break the liquid up into small droplets. Spray nozzles at the inlet offer an opportunity for impaction. Centrifugal force and impingement on the blades are utilized for further collection and water separation. The power requirement is typically in the area of 1.5 k Pa pressure drop when fans are employed on the rotating element. The collection efficiency is generally comparable to other collectors with a similar pressure drop.

An especially high performance type of mechanical scrubber is known as a disintegrator, which consists of a casing that houses a series of rotating and stationary bars. Water is injected axially through the rotor shaft and is separated into fine droplets by the high relative velocity of rotor and stator bars. The particulate-laden gas also enters axially and passes through the dense spray zone where the particulates are subjected to intense bombardment by the fine water droplets. Advantages of this scrubber are high collection efficiency for small particulates and low space requirements. The principle disadvantage is its very large power requirement.

Disintegrators have been employed on blast and electric furnaces, as well as Koppers-Totzek coal gasifiers. Due to close clearances, disintegrators are sometimes subject to particulate buildup problems if the inlet dust loading is high. Then, they are usually preceded by a cyclone or wet scrubber to reduce the particulate loading.

4.2.4 Packed Bed Scrubbers

A tower packed with irregularly shaped objects which resist corrosion may be used for dust and mist collection as well as for gas absorption. The packed bed may be held in place (fixed), free to move (fluid), or covered with water (flooded). The irrigating liquid serves to wet, dissolve, and/or wash the entrained particulates from the bed. This design generally works best for liquid particulates, since solid particles sometimes tend to plug up the bed. Collection efficiencies are typically about 90 percent for particulates of 2 micrometers and larger.

4.2.5 Orifice Scrubbers

This collector atomizes the liquid and forms aerosols by generating high velocities through restricted openings. The gas stream comes into contact with scrubbing liquid at the entrance to a constriction. Liquid is picked up and carried into the restriction where greater liquid-particulate interaction occurs, resulting in high frequency impaction. Upon leaving the restriction, most water droplets disengage from the gas stream by gravity since the gas velocity is greatly reduced downstream from the restriction. Small droplets are subsequently removed by centrifugal force and impingement. The pressure drop for orifice type scrubbers typically ranges from 0.75 to 1.5 k Pa. Collection efficiencies generally approach 90% for particles 2 micrometers or larger.

4.2.6 Impingement Scrubbers

This type of unit produces droplets as the gas passes through wetted perforated plates and impinges on baffles. Here the intention is to expand the surface area of the liquid through use of the gas stream's kinetic energy. One or more impingement baffle stages can be employed, depending on the degree of particulate removal required. A water spray zone is often employed below the bottom plate to cool and humidify the gases and to remove the larger particulate matter. The efficiency and pressure drop of impingement scrubbers are generally comparable to the orifice type.

4.2.7 Venturi Scrubbers

This type of scrubber employs a venturi-shaped constriction and throat velocities considerably higher than those experienced with the orifice type. The high gas velocities at the throat atomize the scrubbing liquid and the turbulence created leads to increasingly high collection efficiencies at increasing energy inputs. Liquid can be supplied at or ahead of the throat through piping or jets. The collection mechanism of the venturi is primarily impaction. As with wet collectors in general, the collection efficiency increases with higher pressure drops. Different pressure drops are achieved by designing for varied gas velocities in the throat. Some venturi scrubbers are manufactured with adjustable throats allowing a range of pressure drops for a given air volume. The collection efficiency of the venturi scrubber can generally be considered highest of the wet collectors.

High energy venturi scrubbers are capable of fine particulate control with an efficiency close to that of fabric filters. As discussed previously, these high energy scrubbers utilize inertial impaction as the principal collection mechanism. The effectiveness of inertial impaction decreases markedly at particulate sizes below 1 micrometer unless high velocity differentials are maintained between the collecting body (water drops) and the particulates. The contribution of inertial impaction could also be enhanced by decreasing the size of the collecting bodies. In both cases, higher energy consumption is required for improving fine particulate collection. Figure 9 shows a typical fractional collection efficiency vs. particulate size for venturi scrubbers (51). It can be seen that the venturi scrubber approaches 100% removal for all particulates larger than 1.5 to 2 micrometers.

In view of its high removal efficiencies, the venturi scrubber has been applied to many difficult collection jobs, including the removal of submicron size iron oxide fumes in the iron and steel industry.

4.2.8 Other Wet Scrubbers

In addition to the commonly used wet scrubbers discussed previously, there are several new scrubber types, including foam scrubbers, steam-assisted scrubbers, and electrostatically augmented scrubbers, that are available for fine particulate removal. The foam scrubber, which combines gaseous absorption along with particulate collection, should be capable of removal of even the very finest particulates with less than twenty inches pressure drop. On commercial installations, electrostatic augmentation has been proved to have achieved both low energy consumption and operating cost. Steam-assisted scrubbers use a considerable amount of energy, but waste heat can be used when available to reduce the net energy consumption and total operating costs. Each of these new types achieves high efficiency on fine particulates, at least under some conditions. At present, the obvious drawback of these designs is their relatively high initial cost compared to the venturi and other types of wet scrubbers, although this initial cost differential may be offset by their lower energy consumption and operating cost. In addition, these newer type scrubbers generally have only a limited amount of operating and performance experience.

4.3 Electrostatic Precipitators

Electrostatic precipitators for cleaning particulates from gases have been used by industry for over seventy years. They have also been found to be an efficient means to detar the gases. Electrostatic precipitators operate by using a high voltage, direct current to create gas ions which impart an electrical charge to particulates by bombardment. The charged particles are collected by exposing them to an electric field, which causes them to migrate and deposit on electrodes of opposite polarity. The electrode cleaning system is dependent upon the type of precipitator. The conventional dry-type precipitator collects

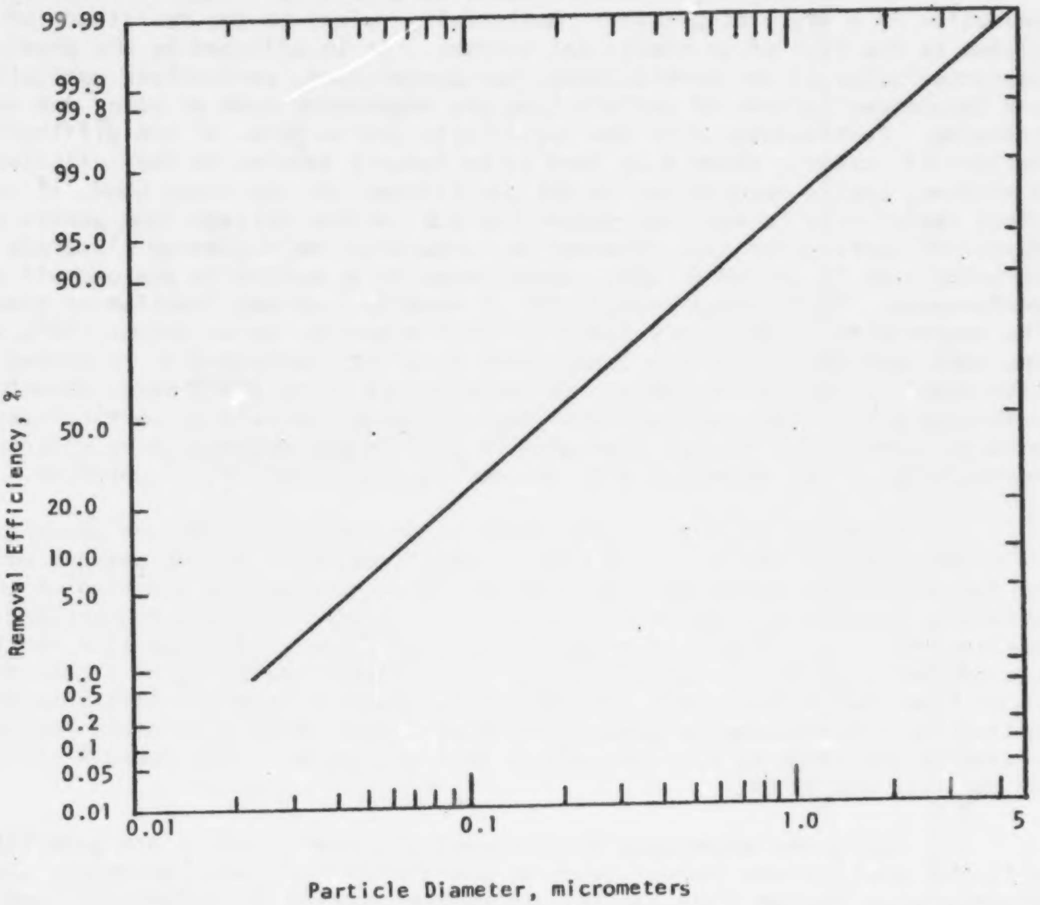

FIGURE 9. Typical Fractional Removal Efficiency of Venturi Scrubbers (51)

particulates on a dry electrode and removes them periodically by mechanical shaking or rapping. Dry precipitators are installed in industries with widely varying gas conditions, temperature, and pressure. The newer wet-type precipitator collects and removes particulates with a thin, continuous flowing film of water. The operating temperatures are generally less than 65°C.

The resistivity of particulates is a critical factor in the design and operation of a dry precipitator. Resistivity refers to the resistance of particulates to the flow of an electrical current. It is affected by the physical characteristics of the particulates, gas temperature, particulate composition, and the concentrations of certain flue gas components such as water and sulfur trioxide. Particulates with low resistivity (below 50 Ω. m) are difficult to collect efficiently since they tend to be loosely adhered to the collector and are, therefore, easily reentrained in the gas stream. On the other hand, if the particulate resistivity is too high (above 0.2 GΩ. m), the voltage drop across the deposited particulate layer becomes so large that the discharge electrode electron emission rate is caused to drop, which leads to a decline in the overall collection performance. Particulate resistivity is usually a strong function of temperature. The resistivity is generally found to reach a maximum value around 150°C, and to decrease continuously as the temperature is either decreased or increased. Hot-side precipitators which operate at temperatures up to 540°C were, therefore, developed for certain applications involving high-resistivity particulates. The moisture content of the gas also affects particulate collection by altering the resistivity, which decreases with increasing concentrations of moisture.

Particle collection efficiency is strongly dependent on the migration or drift velocity, which is the rate at which particles become charged and move to the collecting electrode. In addition to being a strong function of the particle resistivity, the migration velocity is also directly proportional to the particulate size. Figure 10 presents the collection efficiency as a function of particulate size for a high-efficiency precipitator operating on a coal-fired power plant for a field test carried out by Southern Research Institute (52). Collection efficiencies in excess of 90% on a mass basis were noted for particulates in the range of 0.1 micrometers to 1 micrometer. The overall efficiency of the test was 99.6%.

Among the advantages of electrostatic precipitators are generally efficient particulate removal, even at sub-micron sizes and low energy consumption. Disadvantages include high capital and maintenance costs, relatively large space requirements, and greater difficulty in maintaining design collection efficiencies than with many other types of control equipment. Several parameters can significantly lower collection efficiency if they depart from design limitations, including gas volume flow, dust concentration and particle size distribution, resistivity and power levels.

In addition to the more common dry precipitators, wet precipitators have been developed in recent years to solve some of the problems experienced with the dry units. The wet collectors utilize water or some other liquid to wash the dust from the collecting electrodes. The basic principle of precipitator operation is essentially the same for the dry and wet systems, with the major difference being in the method of removing the collected dust.

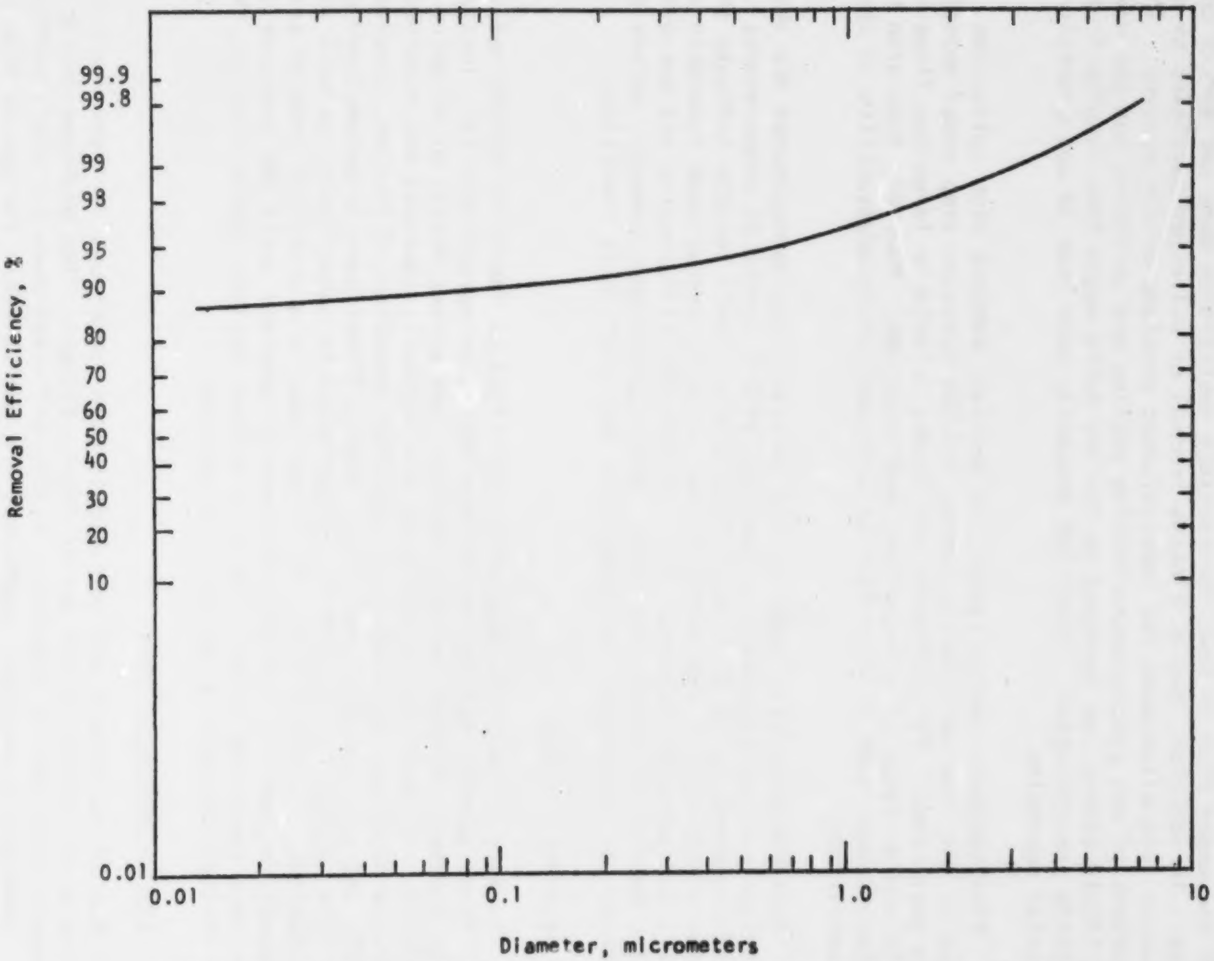

FIGURE 10. Removal Efficiency As A Function of Particle Size for a Typical Electrostatic Precipitator Installation (52)

Wet electrostatic precipitators have an important advantage over dry units in that the efficient collection of a wide range of particulates is enhanced. Since the particulates are generally thoroughly wetted in this type precipitator, they are preconditioned and are effectively charged and precipitated, regardless of the degree of resistivity of the material. Since the resistivity of the water film is low, the particle resistivity does not affect collection efficiency. In addition, the continuous removal of collected particles by the flowing water film eliminates the reentrainment problems of dry systems. The principal problems of wet precipitators involve scaling and corrosion and the need to handle a liquid slurry, as compared to the dry solid waste that results from dry electrostatic precipitation. There are presently more than 30 wet precipitators in commercial operation.

Electrostatic precipitators, in general, exhibit high collection efficiency in the fine particulate range, and low pressure drop under normal operating conditions. Precipitators can handle relatively large gas flows and operate in a wide range of temperatures and pressures. However, they also have major disadvantages such as high initial cost and little adaptability to changing process conditions.

Research-Cottrell, under an EPA contract, has demonstrated the ability of an electrostatic precipitator to generate stable corona at temperatures up to 1093°C and pressures up to 51.5 MPa. Furthermore, their results indicate that conditions for electrostatic precipitation may actually become more favorable as temperature and pressure increase (53). Collection efficiencies and operational reliability need to be determined under these conditions, however, before precipitators can be considered for commercial use under these conditions.

4.4 SURFACE FILTERS

Surface filters are generally classified as fabric or porous medium filters. These control devices use either fabric or porous material, including natural or synthetic fibers, ceramic fabrics, and porous metals or ceramics as the filter medium. In general, particulates are initially captured and retained on the filter medium by direct interception, inertial impaction, diffusion, electrostatic attraction, and gravitational settling. Once a filter cake is accumulated on the upstream side, further collection is accomplished by cake sieving as well as the above mechanisms. In large part, the filter cake is a principal mode of particulate separation, and its growth is allowed to continue until the pressure drop increases to a specified value. Cleaning methods include fabric flexing, reverse air flow through the medium, and solvent washing.

4.4.1 Fabric Medium Filters

One of the oldest and most widely used techniques for removing particulates from a gas stream is the use of fabric filters. The baghouse design is very commonly used, and is inherently highly efficient even for small particulates. However, commercially available baghouses are not suitable for use at high temperatures. A number of high temperature resistant ceramic fabrics have become commercially available. Due to the lack of a suitable high temperature, inorganic fiber lubricant needed for the fiber-to-fiber abrasions, many of these developed ceramic fabrics are presently unsuitable for filtration purposes. Still, ceramic fabric filters offer a potentially promising solution to the problem of controlling particulates in the high-temperature, high-pressure environment. Typical fractional collection efficiencies as a function of particulate size for fabric filters are shown in Figure 11.

4.4.1.1 Baghouses There are two major types of baghouses. Envelope-type bags provide maximum surface area per unit volume, but suffer from dust bridging problems. Tubular bags are open at one end and closed at the other, with the direction of filtering being either inside-out or outside-in. Tubular filter bags are often sewn together to form multibag systems.

Different gas characteristics require different filter media for proper operation. Two basic types of material are commonly used in baghouses, consisting of woven and felted fabrics. Woven fabric acts as a support on which a layer of dust is deposited to form a microporous layer capable of removing additional particulates by sieving and other basic filtration mechanisms. Felted fabrics are complex, labyrinthine masses of randomly oriented fine fibers. The relative thickness provides the advantages of maximum particulate impingement and changes of direction of flow to entrap fine particulates. Felted fabric filters usually can be operated with higher air to cloth ratio than woven fabric filters.

Baghouses have been applied to many industries. In the case of the electric power utility industry, increasing attention is being paid to baghouses, though only a few plants presently employ them. With increasing emphasis on burning low sulfur coal, which often results in reduced efficiencies of electrostatic precipitators, baghouses have become a possible alternate for particulate control. The most recent installations of baghouse filters at the Nucla Station of Colorado-Ute and the Sundbury Station of Pennsylvania Power and Light have been proven to be successful (54) (55). Extensive tests performed at the Nucla Station show overall collection efficiencies greater than 99.9% with exit grain loadings of less than 1.1 cg/m^3. The cleaning part of the operational cycle contributes most to the emissions. The baghouse was found to be very efficient in collecting submicron particulates.

The advantages of baghouse filters include very high collection efficiencies, even for sub-micron particles, relatively low energy use and pressure drop (typically less than 7.5 k Pa), and particles collected in dry form, which simplifies ultimate waste disposal. Disadvantages include large space requirements, high initial costs, and proven temperatures limited to about 290°C.

4.4.1.2 Ceramic Fabric Filters Filtration by conventional fabrics has proven to be highly efficient in controlling particulates at low temperature and pressure. To achieve the same level of collection efficiency at high temperature and pressure, ceramic fabric filters appear to be promising. Advantages of ceramic fibers over conventional fibers are as follows: (1) a number of commercially available ceramic fibers have been found to be functional in high-temperature environments; and (2) ceramic fibers have finer diameters than conventional fibers, usually about 3 micrometers for ceramics vs. 10 to 20 micrometers for conventional fibers. By examining those particulate removal mechanisms which apply to fabric filtration, the increase in removal efficiency by the use of smaller diameter fibers should

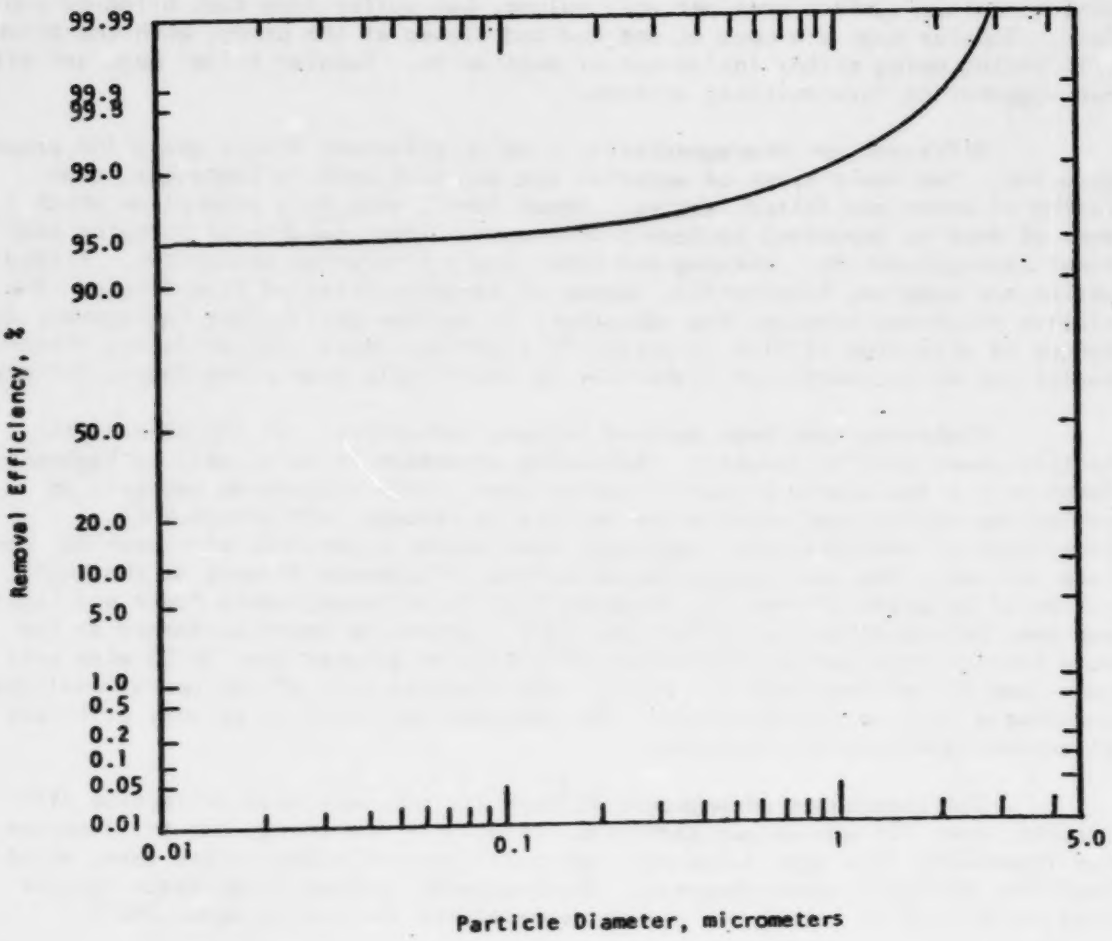

FIGURE 11. Typical Fractional Removal Efficiency of Fabric Filters (51)

compensate for the reduction of efficiency caused by high temperature and pressure. Nevertheless, difficulties with the filter house and cleaning mechanisms have to be solved before ceramic filters can be commercialized. Currently, Acurex Aerotherm, under EPA contract, is investigating the suitability of commercially-available ceramic fabrics for high temperature filtration. Preliminary results from their ambient tests confirm that some of the available ceramic materials appear to have good filtration properties. It was also concluded that innovative cleaning and media support techniques can be designed to be compatible with the special properties of ceramic media (56).

4.4.2 Porous Medium Filters

Porous materials suitable as filter media are commercially available for filtering particulates from gases at high temperatures. Two categories of porous medium filters have been under development, including porous ceramic and metal filters.

4.4.2.1 Porous Ceramic Filters Recently, efforts have been devoted to the development of porous ceramics for high temperature and high pressure filtration. These materials offer the advantages of high melting temperature and mechanical strength, low thermal expansion, and compatability with corrosive environments.

In a two dimensional representation, ceramic membrane filters may be thought of as a uniform solid phase interspersed with a fluid phase (holes), and are generally characterized by low porosity as compared to fiber filters. In a simplified view, membrane filters work because the membrane pore diameter is smaller than that of the particulates to be collected; the particulates are thus prevented from passing through the membrane.

Westinghouse Research Laboratory, under funding by EPA, is currently performing a large scale effort directed towards applying ceramic filters to particulate removal from gas streams at high temperatures (57). This experimental work has been carried out in two phases. Phase I investigated the development and use of membrane type ceramic materials as hot gas filters. The first part of the effort was limited in success due to the fragile nature of the ceramic membranes formed and because it proved to be difficult to control the pore size distribution of the filters. It was concluded that ceramic membrane filters will not be suitable for commercial use in large electric power generating applications.

Phase II examined several commercially available types of ceramic materials, including porous thick-walled filters and thin-walled (0.2 mm) monolithic honeycomb structures. Test results applied to both categories of materials are: (1) filters of this nature are suitable for operation at temperatures exceeding any current coal conversion process requirements; (2) the filters generally exhibit virtually 100% effective removal of a submicron test particulate; and (3) cleaning methods can be devised to allow continuous operation. One of the most promising materials tested was a ceramic crossflow monolith produced by 3M Company under the trademark of ThermaComb. Test results under both ambient and high temperatures (730°C) for ThermaComb are as follows: (1) effective cleaning for continuous operation can be achieved relatively easily with back washing pulses; (2) the filters have relatively low pressure drops at moderate face velocities; (3) the filters have very high surface area to volume ratios, which makes efficient use of pressure vessel containments; and (4) a system based on the use of this type of filter material appears to be viable as a hot gas cleaning system.

4.4.2.2 Porous Metal Filter Porous metal media, in general, have the advantage of durability, in addition to high filtration efficiency. However, porous metal filters require high pressure drop and have low face velocities.

Brunswick Corporation had under development in recent years a porous metal filter for use in high temperature, high pressure application. This device relies on depth filtration, which occurs by particulate capture on individual metal fibers. This approach reduces the pressure drop and enhances throughput. As a result of laboratory tests at ambient conditions, 99% removal efficiency is claimed for 0.3 to 0.5 micrometer particulates at air velocities of 36.6 m/min, or about 25 times normal baghouse air-to-cloth ratios. While the filter could be adequately cleaned over a short time period, the pressure drop across the filter was found to gradually increase to unacceptable levels as the number of filtration-cleaning cycles increased. A suitable cleaning method to enable operations over long periods of time was not identified in the development program. Due to the lack of a viable cleaning method, Brunswick has discontinued this development work on their Brunsmet filter (58).

4.5 GRANULAR BED FILTERS

A granular bed filter employs a stationary or moving bed of granules, sand, gravel, coke or sintered material, as the filter medium. In order to maintain a steady operating performance, a granular bed filter needs to remove the collected particulates from the collecting surface. Several different designs are reported in the technical literature. In general, they may be classified as continuously moving, intermittently moving, or fixed bed filters with respect to the cleaning methods.

Granular bed filters are a promising technique for high temperature and pressure operation. They have the advantages of being able to use either inert or sulfur-absorbent material, and being able to accomodate high face velocities while incurring a moderate pressure drop. In addition, they have the potential to achieve the same high collection efficiency as fiber filters while being somewhat easier to clean. The collection mechanism is similar to that of fiber filters, with impaction predominating and particulates being collected in the interstices of the filter. After the initial collection at the filter surface produces a filter cake, further collection is essentially accomplished by cake sieving. Most recently, granular bed filters have received increased attention, and a number of research projects are underway to further develop these systems. Each class of granular bed filters is discussed below.

4.5.1 Fixed Bed Filter

The fixed bed filter removes collected particulates periodically by either a back flow of clean gas or mechanical shaking. The bed material itself is not moved or replaced. The Ducon and Rexnord Filters are examples of this type, and are discussed below.

4.5.1.1 Ducon Filter The Ducon filter employs screens to retain the granular bed particles while permitting removal of the collected particulates by a blow back technique. The arrangement and operation of the unit is shown schematically in Figure 12.

Performance correlations developed from data on cat-cracker regenerator off-gases show that the Ducon filter achieved overall collection efficiencies ranging from 85% to 98% at temperatures around 480°C (60). Other tests on the Ducon filter have been conducted by Westinghouse, Bureau of Mines, and IGT, with efficiency of 99% reported (47). However, no specific grade efficiency data are available. Exxon Research and Engineering Company is currently evaluating the Ducon filter for reducing emissions of particulates in the flue gas from pressurized fluidized bed coal combustion at high temperature and pressure (530°C, 1MPa) (61). Stable operation for up to 24 hours was demonstrated with a collection efficiency of about 90%. Principal problem areas involve filter cleaning at system conditions, filter plugging and loss of filter media.

4.5.1.2 Rexnord Filter The Rexnord gravel bed filter consists of granular filter beds in conjunction with a mechanical collector,as shown schematically in Figure 13. After the raw gas enters the unit, it initially passes through a cyclone collector which separates the large coarse particles. The precleaned gas rises from the cyclone through a vortex tube and then flows downward through annular gravel beds so that the remaining fine particulates are deposited on the quartz grains and in the interstices of the bed. To clean the filter, the unit uses a raked-shaped double-arm stirring device to loosen the filter cake, and a backwash of clean air to blow the particlesout of the bed.

The results of tests performed on a full scale Rexnord filter system used for controlling particulate emissions from a Portland cement plant clinker cooler were reported by J.D. McCain (62). The system consisted of eight filter units. During normal operation, seven of these eight units were on-line in the forward flow direction, with one being cleaned and renewed by backflushing with heated ambient air. These tests were performed at temperatures from 74°C to 130°C and at atmospheric pressure. The collection efficiency of the Rexnord filter determined by standard mass train techniques on a source producing particulates having a mass median diameter of about 200 micrometers ranged from 95% to 98% during three days of testing, throughout which the collector was not operating in an optimum mode. Overall efficiencies determined from cascade impactor data during a second two-day test series under an improved operating mode were found to be 99.4% and 99.7%. Fractional collection efficiencies as determined using the cascade impactors are shown in Figure 14. The poor collection efficiency of particulates less than 1 micrometer in size is due to the attrition of particulates which occurs during backwash and raking cycles.

Gravel bed filters, designed to treat 127 m^3/min, are commercially available. The unit utilizes mild steel construction and can operate up to 370°C. Rexnord is currently seeking funding to develop a filter for high temperature and pressure operation,(i.e. 870°C, 1 M Pa).

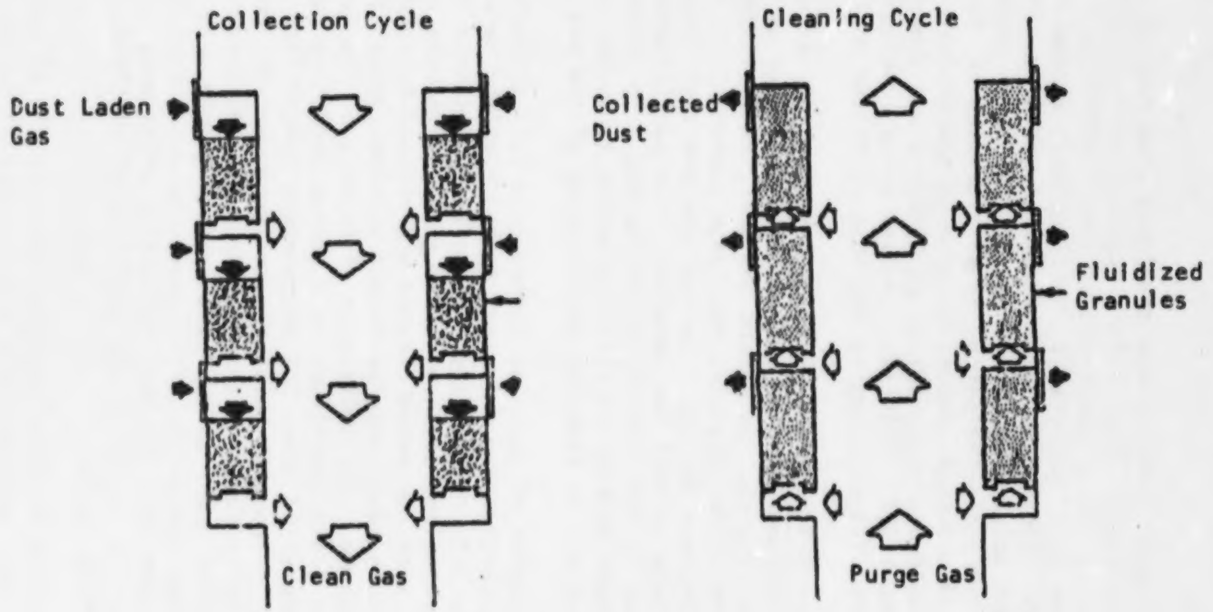
Collection Cycle
Dust Laden Gas
Clean Gas
Cleaning Cycle
Collected Dust
Fluidized Granules
Purge Gas

FIGURE 12. Schematic Illustration of Ducon Filter (59)

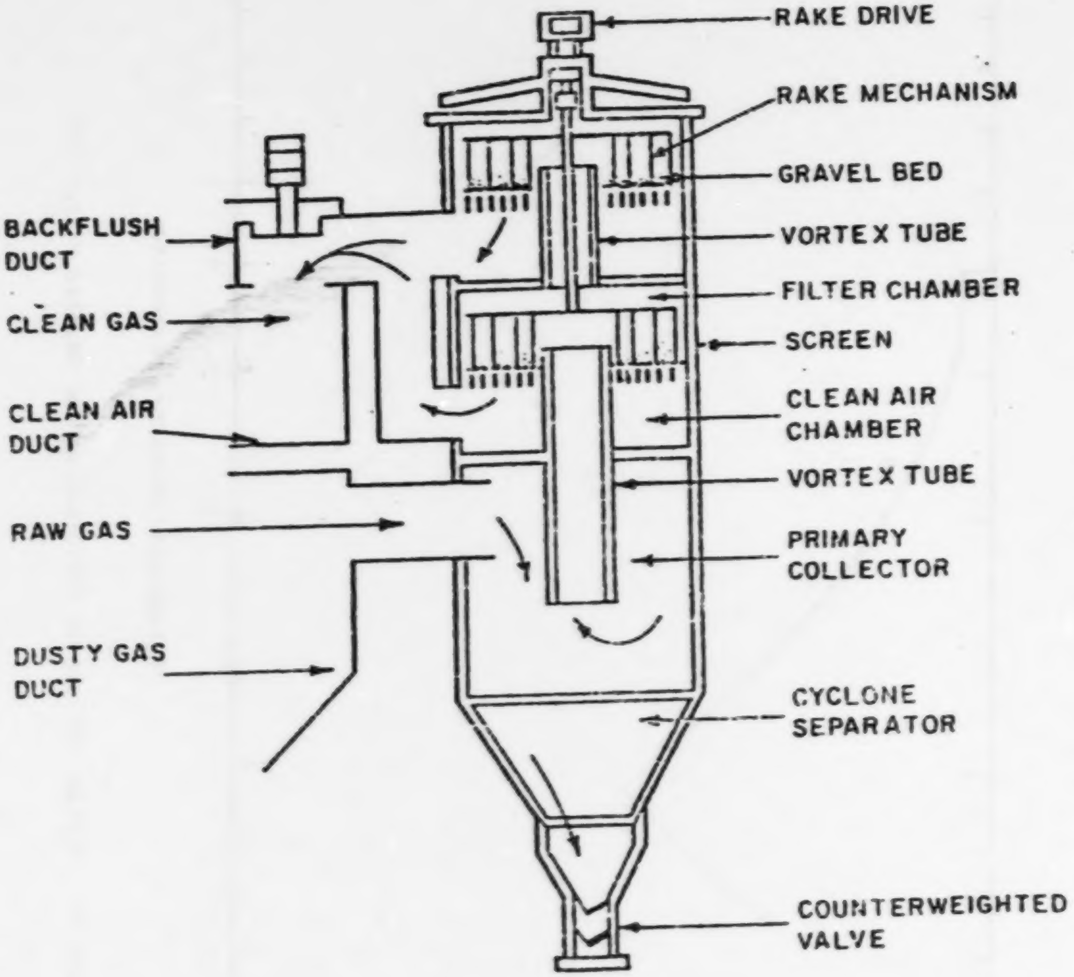
RAKE DRIVE
RAKE MECHANISM
GRAVEL BED
BACKFLUSH DUCT
VORTEX TUBE
FILTER CHAMBER
CLEAN GAS
SCREEN
CLEAN AIR DUCT
CLEAN AIR CHAMBER
VORTEX TUBE
RAW GAS
PRIMARY COLLECTOR
DUSTY GAS DUCT
CYCLONE SEPARATOR
COUNTERWEIGHTED VALVE

FIGURE 13. Rexnord Gravel Bed Filter (59)

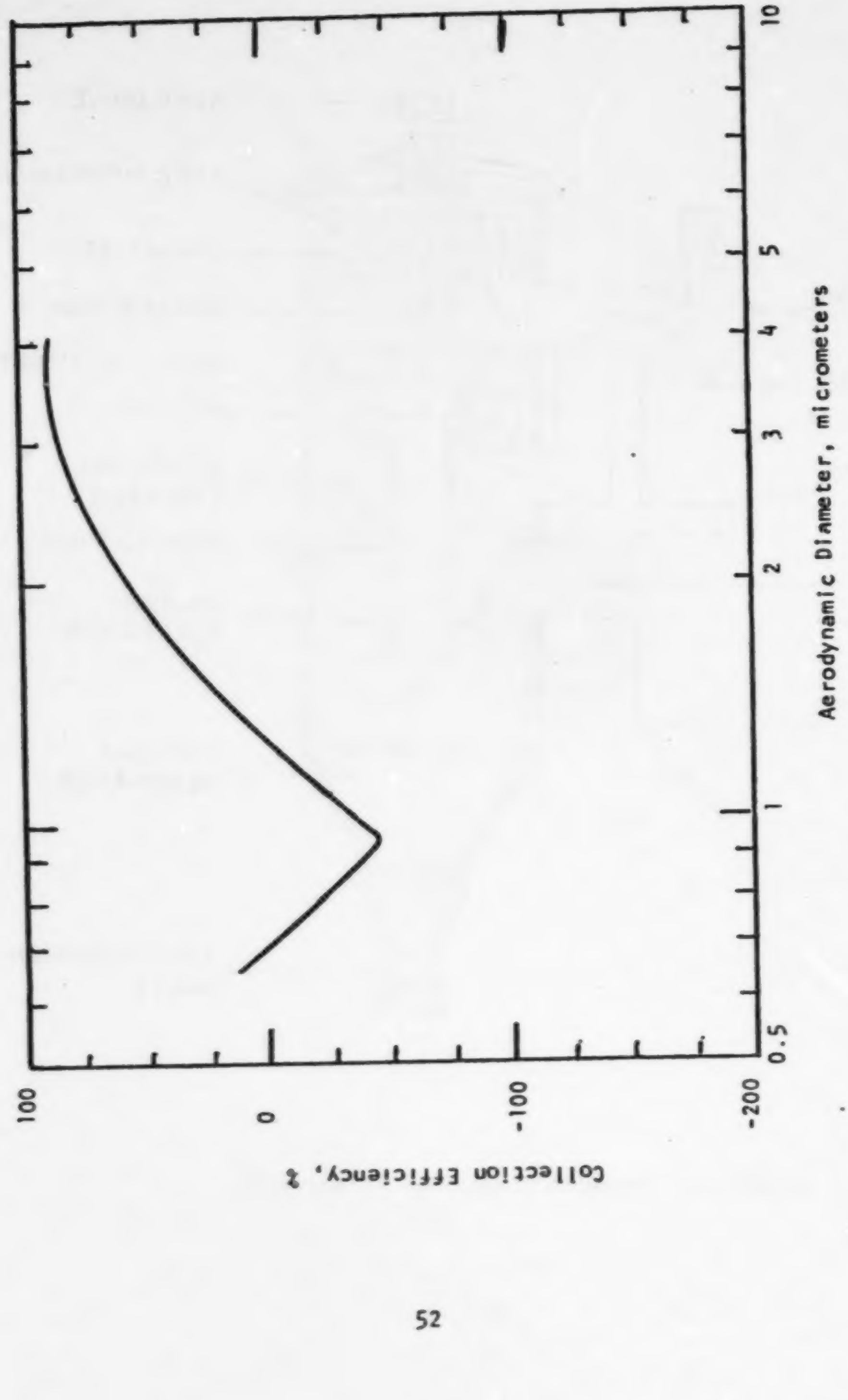

FIGURE 14. Typical Collection Efficiencies for Rexnord Filter (62)

4.5.2 Intermittently Moving Bed Filter

The intermittently moving bed filter uses periodic cleaning to remove filter cake along with a portion of the granular medium in the bed. The Squires panel bed filter is representative of this type and is discussed below.

4.5.2.1 Panel Bed Filter The panel bed filter was developed at City College of New York under the direction of Prof. A.M. Squires. This filter uses two grades of sand which form two vertical walls contained in an open, louvered framework, as illustrated in Figure 15. Fine sand exposed to a dirty gas provides the surface for filter cake formation. Coarse sand, separated from the fine sand by a series of closely spaced horizontal plates, acts as a baffle to contain the fine sand. Cleaning is done by a puffback technique, which consists of interrupting the flow of dirty gas to be filtered, and then passing a clean purge gas in the reverse direction across the panel. This reverse surge creates a mass movement of the sand bed toward the gas-entry face causing sand from each gas-entry surface to spill. This spilled sand carries with it the deposited particles accumulated during the filtration step prior to cleaning. The expelled sand is immediately replaced by downward movement of fresh sand from the overhead hopper.

In laboratory tests with redispersed power station fly-ash, the panel bed was found to afford high filtration efficiencies (beyond 99.95% removal of fly ash) at 150°C, with practicable gas throughput and pressure drop. Efficiency in these tests for removal of sub-micron particulates is estimated at beyond 99%. This estimate was supported by separate experiments employing a monodisperse aerosol of 1.1 micrometer particulates (63). In a high temperature application (540°C) at the Morgantown Energy Research Center, overall collection efficiencies in the range of 95-96% have been recorded. No specific grade efficiency data are available (5). The panel bed filter has gone through the bench-scale stage of development. There is a need to further test the system in more rigorous conditions to ensure the reliability of the system. However, no future work is scheduled, as further support is being sought.

4.5.3 Moving Bed Filter

The moving bed filter removes collected particulates by circulating part of its bed media continuously. The Combustion Power Company has developed a cross flow moving pebble bed filter which is discussed in the following section.

4.5.3.1 Combustion Power Company Filter The Combustion Power Company's moving bed filter and its media circulation loop are illustrated schematically in Figure 16. The unit houses an annular filter element which retains the granular filter media between two vertical, louvered screens. As the raw gas passes through the filtering media, internal impaction removes entrained particulates from the gas which then emerges into an interior collection plenum. The collection of particulates is accomplished by depth filtration, which occurs by particulate capture on individual granules in the bed. To avoid particulate saturation, the media is continuously recirculated and cleaned,using a gravity-bed recirculation system.

Preliminary data from an ongoing experiment on moving bed filtration have been presented by G.L. Wade (64). The results of a linear regression analysis of

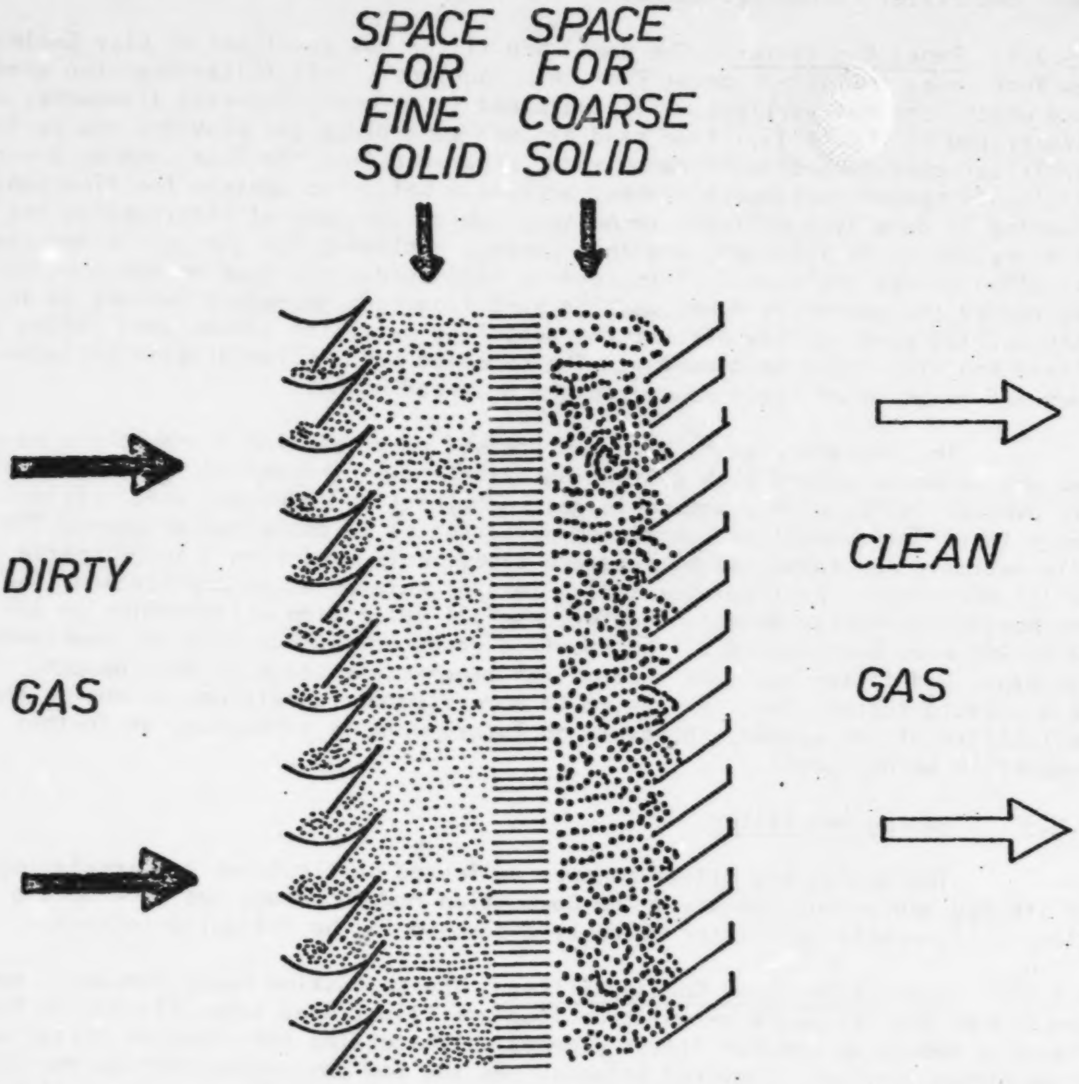
SPACE FOR FINE SOLID
SPACE FOR COARSE SOLID
DIRTY GAS
CLEAN GAS

FIGURE 15. CROSS SECTION OF PANEL BED FILTER (63)

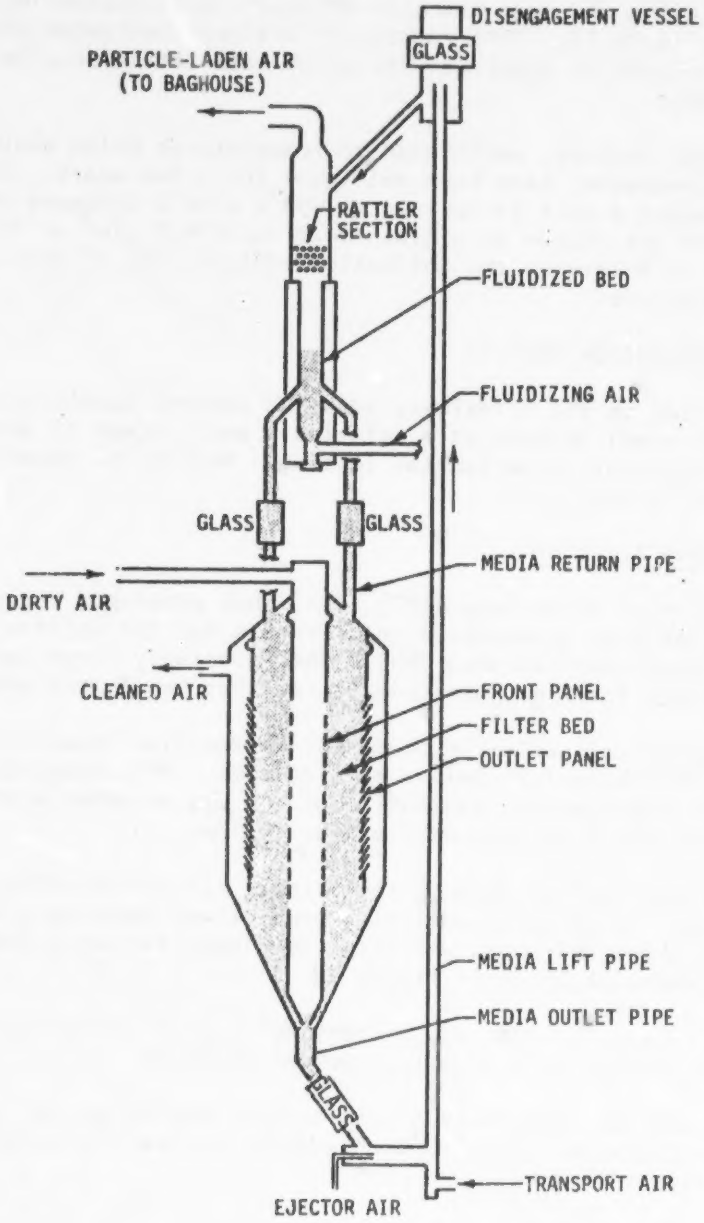
DISENGAGEMENT VESSEL
GLASS
PARTICLE-LADEN AIR (TO BAGHOUSE)
RATTLER SECTION
FLUIDIZED BED
FLUIDIZING AIR
GLASS
GLASS
MEDIA RETURN PIPE
DIRTY AIR
CLEANED AIR
FRONT PANEL
FILTER BED
OUTLET PANEL
MEDIA LIFT PIPE
MEDIA OUTLET PIPE
GLASS
TRANSPORT AIR
EJECTOR AIR

FIGURE 16. Combustion Power Company's Moving Bed Filter (64)

collection efficiencies vs. mean diameter of inlet particulates for 45 cold flow tests is shown in Figure 17. This regression analysis indicates that reasonable operating conditions may be specified for which total efficiency in excess of 95% is readily attainable.

Commercial devices, restricted to temperatures below about 430°C and to pressures near atmospheric, have been available for a few years. Combustion Power Company has fabricated a unit to operate at 650°C with a pressure of a 1 MPa and treat a 11.8 m^3/min gas stream at a grain loading of 9.2 g/m^3 or less. Further testing is needed to determine the collection efficiencies of this unit at high temperature and pressure.

4.6 OTHER COLLECTION DEVICES

In addition to the relatively advanced control technologies previously discussed, several novel devices at a relatively early stage of development have undergone some preliminary experimental testing. Several of these novel devices are discussed briefly below.

4.6.1 A.P.T. Dry Scrubber

Air Pollution Technology (APT), Inc., has developed a dry scrubber system which can be used at high temperature and pressure for the collection of fine particulates on larger particulates (65). The relatively large particulates used as collection centers for fine particulates can then be cleaned and recycled.

Particulate collection is primarily by inertial impaction, and to a lesser extent,by diffusion for smaller particulates. APT, supported by EPA, has done a preliminary experimental evaluation of the dry scrubber system. Some preliminary conclusions from this work are as follows:

- The experimental data on the primary collection efficiency of the system agree well with predictions based on a mathematical model which was first developed for wet scrubbers. The data are shown in Figure 18.
- The system has the same primary collection efficiency/power relationship as a venturi type wet scrubber.
- The overall efficiency of the system depends on the re-entrainment characteristics of the specific system, in addition to the primary efficiency.

4.6.2 Molten Salt Scrubber

Battelle Memorial Institute is developing a molten salt scrubbing technique for removal of both particulates and sulfur compounds from producer gas. This technique is based on the use of a molten alkali salt as the scrubbing liquor in a conventional venturi scrubbing apparatus. Particulate removal in the venturi scrubber is effected by particulate inertial impaction onto molten salt droplets.

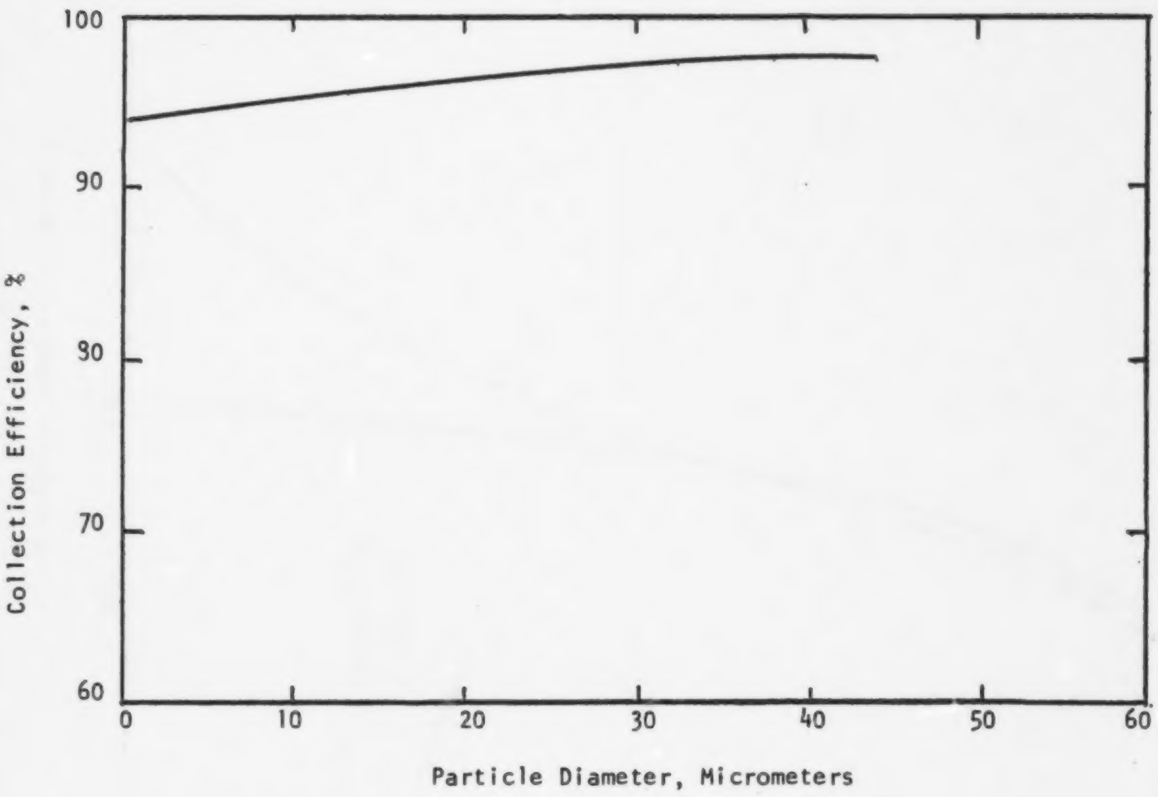

FIGURE 17. Collection Efficiency of Combustion Power Company's Moving Bed Filter (64)

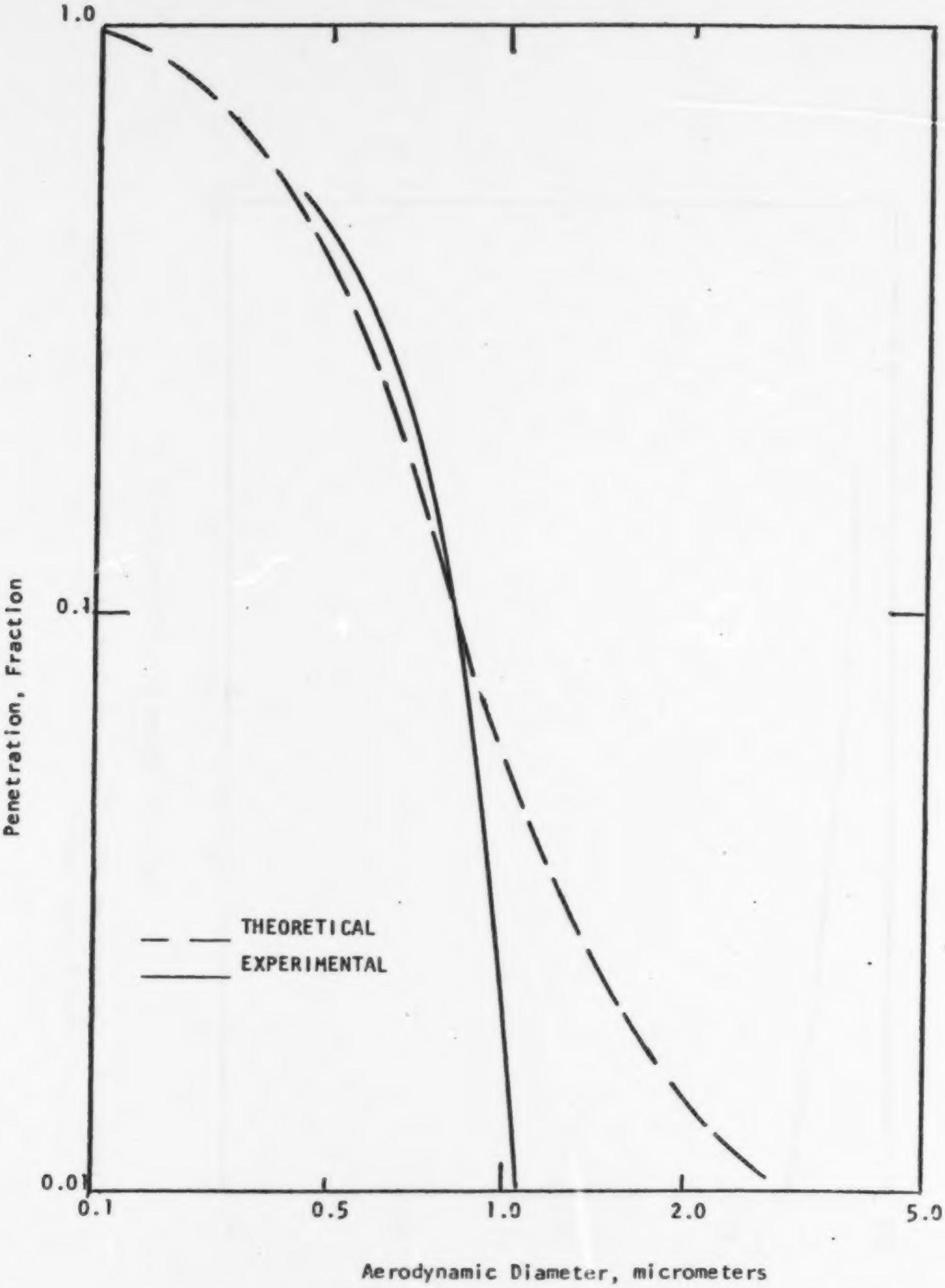

FIGURE 18. Comparison of Experimental and Theoretical Particle Collection Characteristics of the A.P.T Dry Scrubber (65)

As is true with any venturi scrubber, this molten salt scrubber has the advantage of a potentially high collection efficiency. However, there are some unique problems associated with this design: (1) the corrosiveness of the scrubbing alkali medium presents a difficult material handling problem; (2) molten salt decomposes at 900°C and reacts with other gaseous pollutants; (3) carryover of molten liquid droplets; and (4) high energy requirements.

Under DOE funding, Battelle has designed a process demonstration unit for operation in a fully continuous mode (66). Preliminary data show that the overall collection efficiency of the molten salt scrubber is not as great as expected. This reduced efficiency is largely attributable to the re-entrainment of droplets of the scrubbing liquor. This project,however, has been discontinued recently. A final report is being prepared by Battelle. There are no plans for further research.

4.6.3 Electrofluidized Bed Collector

An electrofluidized bed collector was developed by K. Zahedi and H.R. Melcher (67) for the removal of submicron particulates. In this device, an electric field is imposed on a fluidized bed of particles by means of external electrodes, thus causing a polarization of the bed particles, which in turn acts as the collecting electrode. This device is designed to collect fine particulates with high efficiency, and is reported to have potential applicability in the high temperature and pressure domain.

There are three general stages to the gas cleaning process in this device, as in the case of a conventional electrostatic precipitator. First, the particulates are transferred from the gas to the surface of the bed particles. Second, agglomerates of the captured particulates are formed as a result of adhesion on the bed particles. Finally, the agglomerates are removed by means of the outflow of pollutant in a fluidized state.

The electrofluidized bed is still largely in the research stage. Preliminary results show promise of its being extremely effective in removing fine particulates at temperatures up to at least 200°C and at atmospheric pressure.

4.6.4 Charged Filter

This device, which combines the principles of electrostatic precipitation and fabric filtration has been developed by American Precision Industries, Inc. and is called the "Apitron". It provides high efficiency performance, and may be applicable to high temperature flue gas systems with the development of fabrics suited to high temperature operation.

The Apitron device is essentially a wire-tube precipitator with a concentric bag filter and charged screen. The first stage of this device performs as a high velocity precipitator which charges all particulates, while removing about 90% of the total. The fine particulate matter is then collected by the fabric filter in a manner that permits velocities four to five times those used in conventional baghouses.

Recently the EPA has conducted an extensive evaluation of the Apitron system. Efficiencies of 99.99% for 0.1 micrometer particulates have been obtained in the tests. Figure 19 shows a typical sub-micron collection efficiency curve (68).

In addition to its efficient fine particulate collection, the Apitron has the advantage that its electrostatic charging promotes the development of a more loosely packed, porous dust layer on the fabric, permitting air cloth ratios to be increased by a factor of 2 to 5. This results in an overall equipment size reduction of similar proportions.

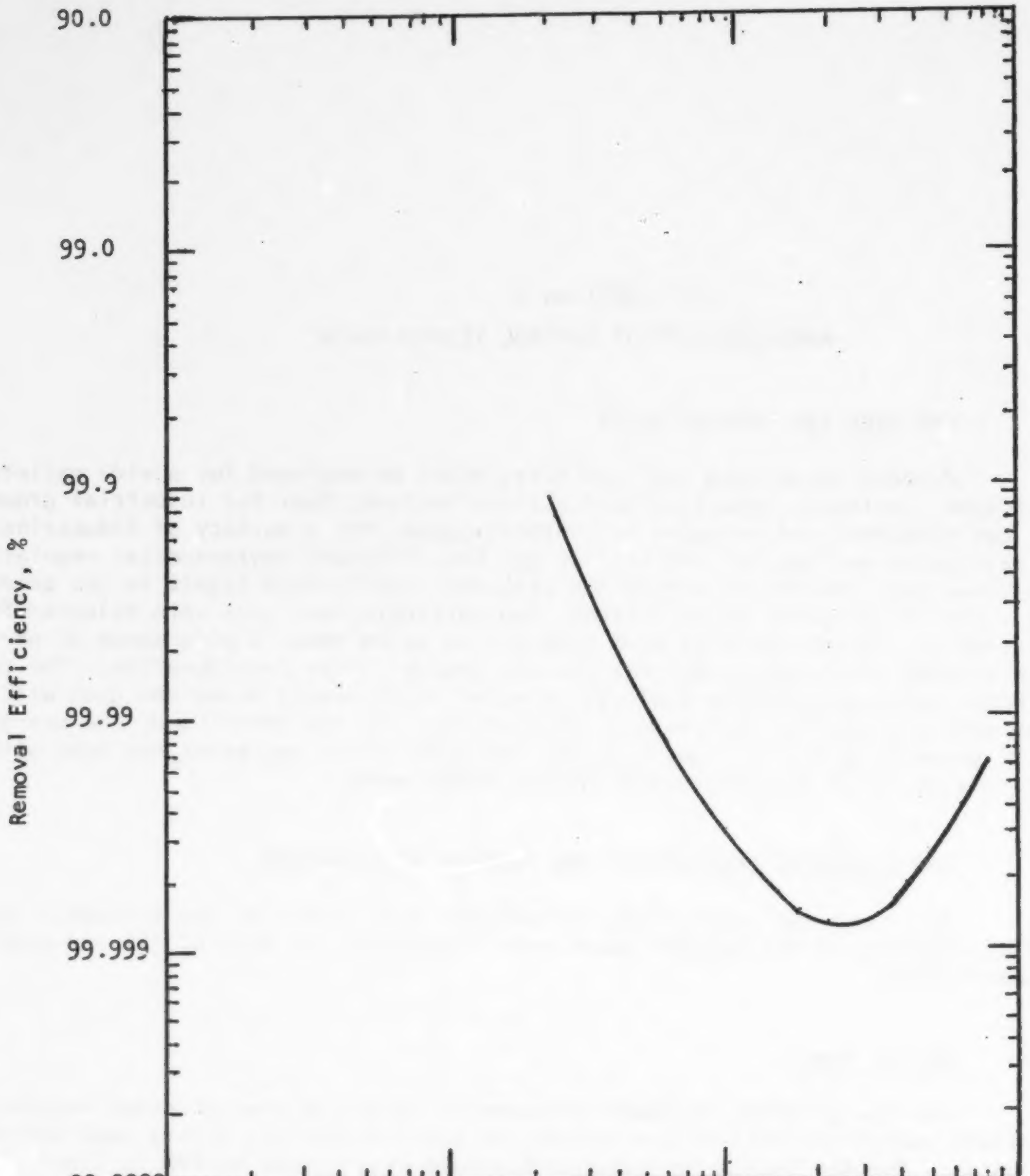

FIGURE 19. Fractional Removal Efficiency of Apitron Charged Filter (68)

SECTION 5

APPLICABILITY OF CONTROL TECHNOLOGIES

5.1 END USES FOR PRODUCT GASES

Product gases from coal gasifiers might be employed for a wide variety of end uses, including industrial and utility boilers, fuel for industrial process heat, gas turbines, and reducing or synthesis gases for a variety of industries. Each particular end use for the product gas has different environmental regulations and process requirements governing the allowable particulate levels in the product gases. For the purposes of this study, two particular end uses were selected for consideration. These end uses were selected so as to cover a wide range of particulate removal requirements for the control devices under consideration. The use of product gases as a boiler fuel was selected to represent those end uses with low to moderate particulate cleanup requirements. On the other hand, the use of product gases as a fuel for gas turbines was selected to represent end uses with relatively restrictive particulate removal requirements.

5.2 ENVIRONMENTAL REGULATIONS AND PROCESS REQUIREMENTS

Environmental regulations and process limitations on the allowable particulate contents of the product gases were identified for each of the end uses discussed above.

5.2.1 Boiler Fuel

For the purposes of these assessments, existing environmental regulations for direct coal-fired boilers are assumed to apply to boilers firing coal-derived fuel gases. The New Source Performance Standard established by EPA to limit particulate emissions from fossil-fuel fired steam generators is 43 nanograms per Joule heat input (0.10 lb/10^6 Btu). This is equivalent to 0.24 grams of particulates per cubic meter for low-Btu fuel gas with an average heating value of

0.56 MJ/m^3 (150 Btu/scf), or 0.48 grams of particulates per cubic meter for medium-Btu fuel gas with a heating value of 1.12 MJ/m^3 (300 Btu/scf). Thus, depending on the heat content of the gas to be used in the boiler fuel and assuming that combustion of the fuel gas adds only a negligible amount of particulates, the particulate removal system that is selected might have to remove particulates down to a level as low as 0.24 g/m^3.

Adverse health effects and haze problems are most acute with sub-micron particulates, which generally account for only a very small portion of the total particulate emissions. While present EPA regulations apply only to the total particulate load, future regulations may specifically limit the emissions of the sub-micron size particulates.

5.2.2 Gas Turbines

A particularly promising end use for coal-derived product gases is as a fuel for gas turbines employed in combined-cycle power stations. In a combined cycle, electricity is produced both by expansion of pressurized gases in a gas turbine and by expansion of steam in a steam turbine. The fuel gas would be burned and then expanded in the gas turbine, which generates electricity and also drives the air compressor. The exhaust gases from the turbine can then be used to deliver heat to a steam generator, which drives a steam turbine to produce additional power. Combined cycle plants are generally more energy efficient than comparable conventional power plants.

The tolerance of a gas turbine to particulates is not known with a high degree of certainty. In general, the turbine tolerance for particulates depends upon size and physical and chemical properties. Stringent specifications for fuels to be burned in gas turbines have been established by various turbine manufacturers. The most stringent turbine tolerance established to date is 0.0034 g/m^3 for low- Btu fuel gas, based on an air/fuel ratio of 8/1 with dust-free air and turbine inlet temperature of 980°C (69). However, results of theoretical calculations made by DOE's High Temperature Turbine Technology Program (5) suggest a maximum tolerance of 0.0046 g/m^3 of expansion gas, or 0.041 g/m^3 of fuel gas, with no particulates larger than 6 micrometers. Until more data are developed, these recommendations probably provide the most reliable indication of turbine particulate tolerance. Thus, in these assessments on control technology applicability, the particulate tolerance of the gas turbine will be taken as 0.041 grams of particulates per cubic meter of fuel gas, with no particulates larger than 6 micrometers being allowed. It should be noted that there are presently no environmental regulations governing the emission of particulates from gas turbines.

5.3 PERFORMANCE EVALUATION

The applicability of a particulate control technology for any given end use-gasifier combination is determined by many factors such as the particulate characteristics, cost of control, and system reliability. However, it is important to first determine whether a particulate control technology is capable of meeting the basic requirements of particulate removal before proceeding with more detailed evaluations. Thus, in this section, the applicability of each control technology for the end uses under consideration are evaluated strictly on the basis of the capability of that control technology to achieve the required degree of particulate removal.

A preliminary analysis was first conducted to assess the range of removal efficiencies required for each end use, based on the best, average, and worst-case effluent grain loadings for each gasifier, as discussed in Section 3 and presented in Table 13. This was done by computing the required removal efficiency as a function of particulate loadings for each generic type of gasifier. The results show a quite wide range of removal efficiency is required, as shown in Table 14.

The removal efficiency of any particulate control technology is a strong function of particulate size. Thus, a meaningful applicability assessment of control technologies requires knowledge of the particulate size distribution in the gases to be treated, along with removal efficiencies of the control technologies as a function of particle diameter. Typical particle size distribution curves for each generic gasifier type are presented in Figures 1,2and 3 of Section 3. Typical fractional removal efficiency curves for the generic control technologies under consideration are presented in Section 4. However, in most cases, these removal efficiency curves are limited only to the range of small particulates. This is due to the fact that the removal efficiency is much more dependent on particle size for the smaller particles, with most removal efficiency curves dropping off rapidly at small particle diameters from a nearly constant value at the larger particle sizes. For example, both fabric filters and high efficiency venturi scrubbers are capable of complete removal of particles greater than 6 micrometers under certain operating conditions. However, their removal efficiencies degrade considerably as the particle size decreases to the sub-micron range.

For particulates less than 6 micrometers, a graphical method was used to calculate the mean removal efficiency as a function of particulate size distribution for each gasifier effluent. For the particulates greater than 6 micrometers a representative value of removal efficiency was chosen for each generic control device, with the exception of the conventional cyclone. This is due to the fact that the removal efficiency of a conventional cyclone usually reaches a maximum at a much larger particle size than 6 micrometers, while for most other control devices the removal efficiencies are nearly constant for particles greater than 6 micrometers. Thus, the same general graphical method was used to calculate the mean removal efficiencies of a cyclone for each gasifier effluent over the particulate size ranges below and above 6 micrometers.

The graphical method employed for calculating the mean particulate removal efficiency for particles between 0 and 6 micrometers in diameter is derived from the following equation:

$$E = 1 - \int_0^6 f(Dp)\, d(Dp)$$

Where E = total removal efficiency for particulates less than 6 micrometer,
f = removal efficiency as function of D_p,
Dp = particulate diameter, micrometers.

TABLE 14 PARTICULATE REMOVAL EFFICIENCIES REQUIRED FOR DIFFERENT END USES

Gasifier	Effluent Loading (g/m^3)	Required Removal Efficiencies (%) End Use 1 Turbine Tolerance 0.041(g/m^3)* (before combustion)	Required Removal Efficiencies (%) End Use 2 EPA Emission Standard 0.24(g/m^3) (Low-Btu Gas)
Fixed Bed			
Best Case	0.5	91.80	52.0
Average Case	3.0	98.63	92.0
Worst Case	6.0	99.29	95.9
Fluid Bed			
Best Case	1.2	96.58	80.0
Average Case	26	99.84	99.1
Worst Case	120	99.97	99.8
Entrained Bed			
Best Case	30	99.86	99.2
Average Case	110	99.96	99.8
Worst Case	230	99.98	99.9

* No particles greater than 6 micrometers in diameter are permitted.

The graphical method of integrating this equation is illustrated by the following example for calculating the collection efficiency of a conventional cyclone operating on an effluent with the characteristics of the raw product gases from the MERC fixed bed gasifier burning Illinois #6 coal. Particulate size distribution data for the MERC fixed bed gasifier burning Illinois #6 coal are presented in Figure 1 . Also, data for the fractional removal efficiency of a conventional high efficiency cyclone are presented in Figure 5 . These data were then tabulated, as shown in Table 15 . Figure 20 was then obtained by plotting the last two columns of Table 15. The area under the curve was graphically integrated by determining the point at which the areas above and below the line become equal. An overall removal efficiency of 86 percent for the particulates less than 6 micrometers was thereby obtained.

Table 16 presents a compilation of calculated removal efficiencies for particulates less than 6 micrometers for each combination of generic control device and gasifier effluent. These results were obtained by the graphical method described above. Results are presented for the best, average, and worst-cases of particle size distribution as discussed in Section 3 and presented in Figures 1 through 3. It should be noted that sufficient data were not available for several of the more advanced and recently developed control technologies discussed in Section 4 to estimate their overall particulate collection efficiencies. Results for these devices are, therefore, not presented in Table 16 .

With the overall removal efficiency of each generic control device thus far developed, the applicability assessments were then carried out on the basis of the estimated particulate loadings from each gasifier, as presented in Table 13 . The amount of particulates not removed, and consequently that remain in the product gases, were then calculated. The results for each generic control device under consideration are presented in Tables 17 through 22 . The applicability was determined by comparing the amount of particulates not removed to the maximum allowable amount of particulates for each end use. These results are shown in the last two columns of Tables 17 through 22 .

Conclusions drawn from these results are discussed below separately for End Use 1 (combined cycle fuel gas) and End Use 2 (conventional boiler fuel gas). As for End Use 1, the very restrictive requirement of removing all particles larger than 6 micrometers has limited the potential control devices to fabric filters, a high efficiency venturi scrubber, and the Aerodyne rotary flow cyclone. Among these three control devices, the fabric filter was found to be the only device capable of achieving the required product gas purity for End Use 1 for all gasifier effluents. This requirement is to reduce the concentration of particulates with size less than 6 micrometers to below 0.041 g/m^3 for all cases, as shown in Table 14 . The high efficiency venturi scrubber is applicable for End Use 1 for all gasifier effluents, except for the worst-case fluid bed gasifier, as shown in Table 19 . However, with a high efficiency cyclone upstream as a scalping device, the venturi scrubber is capable of achieving this requirement for the worst-case fluid bed, based on the assumption that the particulate size distribution for particulates less than 6 micrometers remains unchanged after passing through the cyclone. The Aerodyne rotary flow cyclone is found to be inapplicable for the average and worst-case fluid bed

TABLE 15

COLLECTION EFFICIENCY OF HIGH EFFICIENCY CYCLONE FOR PARTICULATES FROM MERC FIXED BED GASIFIER EMPLOYING ILLINOIS #6 COAL

Particulate Size (Dp) micrometers	Amount < Dp,* % by weight	Cyclone Efficiency,** %
16	4	>99
15	3	99
14	2.5	99
13	2.0	98.5
12	1.5	98
11	1.3	97
10	1	96
9	0.7	95
8	0.4	94
7	0.3	92
6	0.25	90
5	0.11	87
4	0.07	83
3	0.02	77
2	0.01	68
1	0.001	53

* Cumulative size distribution data for MERC gasifier.

** Collection efficiency for particles with diameter of Dp.

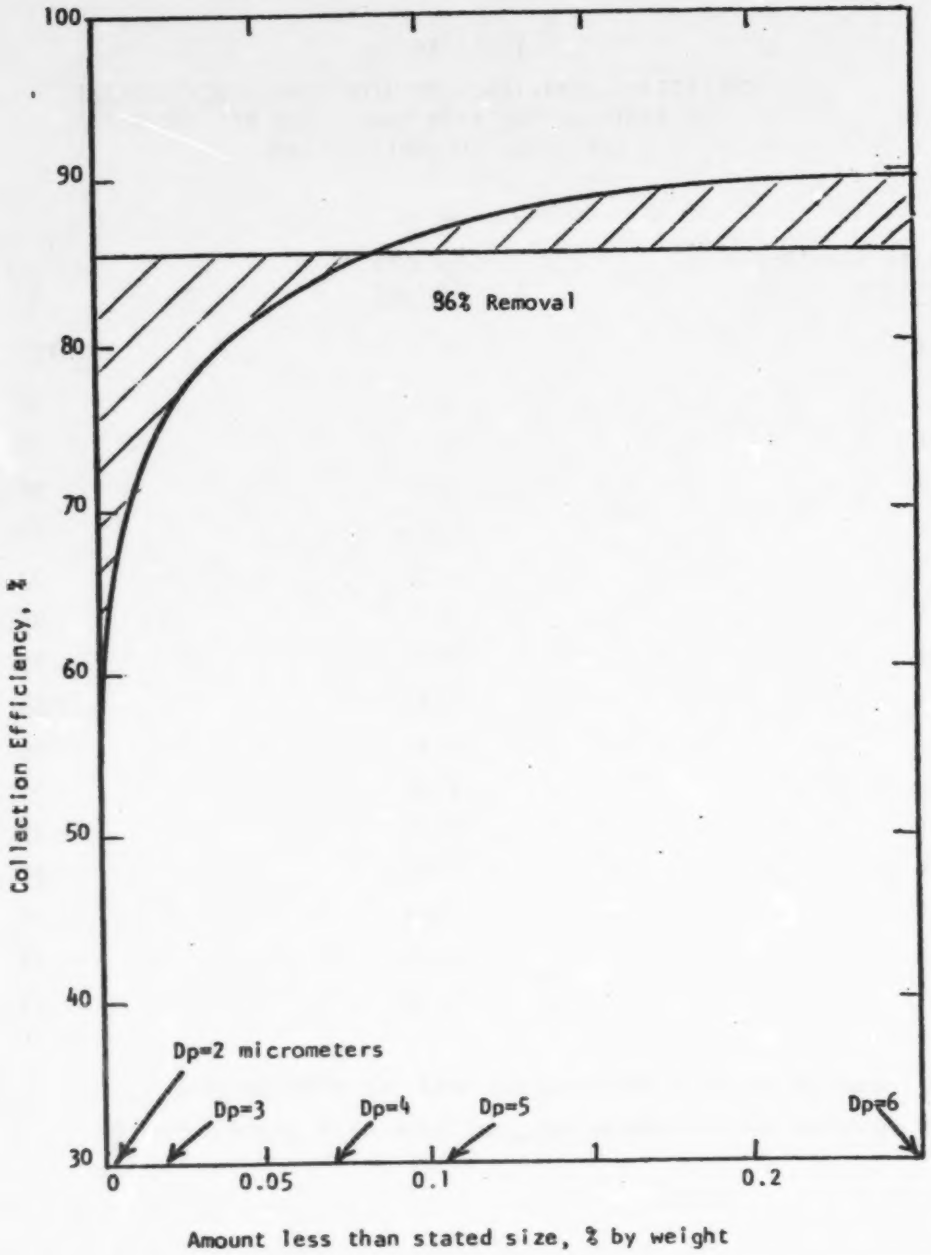

FIGURE 20. Graphical Procedure for Estimating Overall Collection Efficiency For Particulates up to 6 Micrometers in Diameter

TABLE 16

OVERALL PARTICULATE REMOVAL EFFICIENCIES OF GENERIC CONTROL TECHNOLOGIES FOR TYPICAL GASIFIER OUTPUTS

Gasifiers		Particulate Size (μm)	% Particulate Removal Vs. Particulate Size					
			Conventional Cyclone	Rotary Cyclone	Venturi Scrubber	Fabric Filter	E.S.P.	Granular Bed Filter
Fixed Bed	Best Case	<6 >6	86 99	98.5 100	99.93 100	99.99 100	N.A. N.A.	94.6 95
	Average Case	<6 >6	86 98	98.8 100	99.94 100	99.99 100	N.A. N.A.	94.7 95
	Worst Case	<6 >6	86 97	99 100	99.95 100	99.99 100	N.A. N.A.	94.7 95
Fluid Bed	Best Case	<6 >6	82 98.8	90 100	97 100	99.2 100	98 99.8	94.4 95
	Average Case	<6 >6	79 98.7	91.5 100	97.8 100	99.4 100	98.4 99.8	94.5 95
	Worst Case	<6 >6	76 98.5	93 100	98.5 100	99.6 100	98.8 99.8	94.5 95
Entrained Bed	Best Case	<6 >6	84 98.6	96.5 100	99.7 100	99.94 100	99 99.8	94.6 95
	Average Case	<6 >6	83 98.8	97.3 100	99.83 100	99.97 100	99.2 99.8	94.7 95
	Worst Case	<6 >6	82 98.9	98 100	99.95 100	99.99 100	99.4 99.8	94.7 95

TABLE 17 THE APPLICABILITY OF CONVENTIONAL CYCLONE FOR GASIFICATION PROCESSES

		Particulate Loading g/m^3 (gr/scf)	Percent Particulate Distribution		Percent Particulate Removed %	Particulate Not Removed g/m^3	Applicability for Combined Cycle End Use [a]	Applicability for Boiler Fuel End Use[b]
			Size (μm)	%				
Fixed Bed	Best	0.5 (0.22)	<6	0.3	86	0.0003	N.A.	Applicable
			>6	99.7	99	0.0046		
	Average	3.0 (1.31)	<6	5.4	86	0.0023	N.A.	Applicable
			>6	94.6	98	0.0557		
	Worst	6.0 (2.62)	<6	10.5	85	0.0869	N.A.	N.A.
			>6	89.5	97	0.1603		
Fluid Bed	Best	1.2 (0.52)	<6	1	92	0.0023	N.A.	Applicable
			>6	99	98.8	0.0137		
	Average	26.0 (11.36)	<6	3	79	0.1649	N.A.	N.A.
			>6	97	98.7	0.3275		
	Worst	120.00 (52.44)	<6	5	76	1.44	N.A.	N.A.
			>6	95	98.5	1.65		
Entrained Bed	Best	30.0 (13.11)	<6	0.5	84	0.023	N.A.	N.A.
			>6	99.5	98.6	0.419		
	Average	110.0 (48.07)	<6	0.7	83	0.131	N.A.	N.A.
			>6	99.3	98.8	1.312		
	Worst	230.0 (100.51)	<6	0.8	82	0.339	N.A.	N.A.
			>6	99.2	98.9	2.512		

[a] Based on maximum allowable particulate load of 0.041 g/m^3.
[b] Based on maximum allowable particulate load of 0.24 g/m^3.

TABLE 18 THE APPLICABILITY OF A ROTARY CYCLONE FOR GASIFICATION PROCESSES

		Particulate Loading g/m^3 (gr/scf)	Percent Particulate Distribution		Percent Particulate Removed	Particulate Not Removed g/m^3	Applicability for Combined Cycle End Use[a]	Applicability for Boiler Fuel End Use[b]
			Size (μm)	%	%			
Fixed Bed	Best	0.5 (0.22)	<6	0.3	98.5	0.00002	Applicable	Applicable
			>6	99.7	100	0		
	Average	3.0 (1.31)	<6	5.4	98.3	0.0023	Applicable	Applicable
			>6	94.6	100	0		
	Worst	6.0 (2.62)	<6	10.5	99	0.0069	Applicable	Applicable
			>6	89.5	100	0		
Fluid Bed	Best	1.2 (0.52)	<6	1	90	0.0012	Applicable	Applicable
			>6	99	100	0		
	Average	26.0 (11.36)	<6	3	91.5	0.0664	N.A.	Applicable
			>6	97	100	0		
	Worst	120.00 (52.44)	<6	5	93	0.421	N.A.	N.A.
			>6	95	100	0		
Entrained Bed	Best	30.0 (13.11)	<6	0.5	96.5	0.0051	Applicable	Applicable
			>6	99.5	100	0		
	Average	110.0 (48.07)	<6	0.7	97.3	0.021	Applicable	Applicable
			>6	99.3	100	0		
	Worst	230.0 (100.51)	<6	0.8	98	0.036	Applicable	Applicable
			>6	99.2	100	0		

[a] Based on maximum allowable particulate load of 0.041 g/m^3.
[b] Based on maximum allowable particulate load of 0.24 g/m^3.

TABLE 19 THE APPLICABILITY OF A VENTURI SCRUBBER FOR GASIFICATION PROCESSES

		Particulate Loading g/m^3 (gr/scf)	Percent Particulate Distribution		Percent Particulate Removed %	Particulate Not Removed g/m^3	Applicability for Combined Cycle End Use [a]	Applicability for Boiler Fuel End Use[b]
			Size (μm)	%				
Fixed Bed	Best	0.5 (0.22)	<6	0.3	99.93	0	Applicable	Applicable
			>6	99.7	100	0		
	Average	3.0 (1.31)	<6	5.4	99.94	0.0001	Applicable	Applicable
			>6	94.6	100	0		
	Worst	6.0 (2.62)	<6	10.5	99.95	0.0002	Applicable	Applicable
			>6	89.5	100	0		
Fluid Bed	Best	1.2 (0.52)	<6	1	97	0.0005	Applicable	Applicable
			>6	99	100	0		
	Average	26.0 (11.36)	<6	3	97.8	0.017	Applicable	Applicable
			>6	97	100	0		
	Worst	120.00 (52.44)	<6	5	98.5	0.089	N.A.	Applicable
			>6	95	100	0		
Entrained Bed	Best	30.0 (13.11)	<6	0.5	99.7	0.0005	Applicable	Applicable
			>6	99.5	100	0		
	Average	110.0 (48.07)	<6	0.7	99.83	0.0014	Applicable	Applicable
			>6	99.3	100	0		
	Worst	230.0 (100.51)	<6	0.8	99.95	0.0009	Applicable	Applicable
			>6	99.2	100	0		

[a] Based on maximum allowable particulate load of 0.041 g/m^3.
[b] Based on maximum allowable particulate load of 0.24 g/m^3.

TABLE 20 THE APPLICABILITY OF AN ELECTROSTATIC PRECIPITATOR FOR GASIFICATION PROCESSES

		Particulate Loading g/m^3 (gr/scf)	Percent Particulate Distribution Size (μm)	Percent Particulate Distribution %	Percent Particulate Removed %	Particulate Not Removed g/m^3	Applicability for Combined Cycle End Use [a]	Applicability for Boiler Fuel End Use[b]
Fixed Bed	Best	0.5 (0.22)	<6	0.3	--	--	N.A.	N.A.
			>6	99.7	--	--		
	Average	3.0 (1.31)	<6	5.4	--	--	N.A.	N.A.
			>6	94.6	--	--		
	Worst	6.0 (2.62)	<6	10.5	--	--	N.A.	N.A.
			>6	89.5	--	--		
Fluid Bed	Best	1.2 (0.52)	<6	1	98	0.0002	N.A.	Applicable
			>6	99	97.8	0.0002		
	Average	26.0 (11.36)	<6	3	98.4	0.013	N.A.	Applicable
			>6	97	99.8	0.050		
	Worst	120.00 (52.44)	<6	5	98.8	0.071	N.A.	N.A.
			>6	95	99.8	0.227		
Entrained Bed	Best	30.0 (13.11)	<6	0.5	99	0.002	N.A.	Applicable
			>6	99.5	99.8	0.060		
	Average	110.0 (48.07)	<6	0.7	99.2	0.006	N.A.	Applicable
			>6	99.3	99.8	0.210		
	Worst	230.0 (100.51)	<6	0.8	99.4	0.011	N.A.	N.A.
			>6	99.2	99.3	0.456		

[a] Based on maximum allowable particulate load of 0.041 g/m^3.
[b] Based on maximum allowable particulate load of 0.24 g/m^3.

TABLE 21 THE APPLICABILITY OF A FABRIC FILTER FOR GASIFICATION PROCESSES

		Particulate Loading g/m^3 (gr/scf)	Percent Particulate Distribution		Percent Particulate Removed %	Particulate Not Removed g/m^3	Applicability for Combined Cycle End Use[a]	Applicability for Boiler Fuel End Use[b]
			Size (μm)	%				
Fixed Bed	Best	0.5 (0.22)	<6	0.3	99.99	0	Applicable	Applicable
			>6	99.7	100	0		
	Average	3.0 (1.31)	<6	5.4	99.99	0.00002	Applicable	Applicable
			>6	94.6	100	0		
	Worst	6.0 (2.62)	<6	10.5	99.99	0.00006	Applicable	Applicable
			>6	89.5	100	0		
Fluid Bed	Best	1.2 (0.52)	<6	1	99.2	0.00009	Applicable	Applicable
			>6	99	100	0		
	Average	26.0 (11.36)	<6	3	99.4	0.0042	Applicable	Applicable
			>6	97	100	0		
	Worst	120.00 (52.44)	<6	5	99.6	0.0024	Applicable	Applicable
			>6	95	100	0		
Entrained Bed	Best	30.0 (13.11)	<6	0.5	99.94	0.00009	Applicable	Applicable
			>6	99.5	100	0		
	Average	110.0 (48.07)	<6	0.7	99.97	0.00023	Applicable	Applicable
			>6	99.3	100	0		
	Worst	230.0 (100.51)	<6	0.8	99.99	0.00018	Applicable	Applicable
			>6	99.2	100	0		

[a] Based on maximum allowable particulate load of 0.041 g/m^3.
[b] Based on maximum allowable particulate load of 0.24 g/m^3.

TABLE 22 THE APPLICABILITY OF A GRANULAR BED FILTER FOR GASIFICATION PROCESSES

		Particulate Loading g/m^3 (gr/scf)	Percent Particulate Distribution		Percent Particulate Removed %	Particulate Not Removed g/m^3	Applicability for Combined Cycle End Use [a]	Applicability for Boiler Fuel End Use[b]
			Size (μm)	%				
Fixed Bed	Best	0.5 (0.22)	<6	0.3	94.6	0.00008	N.A.	Applicable
			>6	99.7	95	0.0229		
	Average	3.0 (1.31)	<6	5.4	94.7	0.0035	N.A.	Applicable
			>6	94.6	95	0.142		
	Worst	6.0 (2.62)	<6	10.5	94.7	0.033	N.A.	N.A.
			>6	89.5	95	0.269		
Fluid Bed	Best	1.2 (0.52)	<6	1	94.4	0.00067	N.A.	Applicable
			>6	99	95	0.025		
	Average	26.0 (11.36)	<6	3	94.5	0.0419	N.A.	N.A.
			>6	97	95	1.218		
	Worst	120.00 (52.44)	<6	5	94.5	0.318	N.A.	N.A.
			>6	95	95	5.422		
Entrained Bed	Best	30.0 (13.11)	<6	0.5	94.6	0.0077	N.A.	N.A.
			>6	99.5	95	1.972		
	Average	110.0 (48.07)	<6	0.7	94.7	0.0397	N.A.	N.A.
			>6	99.3	95	5.281		
	Worst	230.0 (100.51)	<6	0.8	94.7	0.095	N.A.	N.A.
			>6	99.2	95	10.95		

[a] Based on maximum allowable particulate load of 0.041 g/m^3.

[b] Based on maximum allowable particulate load of 0.24 g/m^3.

gasifier, as shown in Table 18. By considering a cyclone upstream as a scalping device, the Aerodyne rotary flow cyclone was found to be capable of meeting the requirement of End Use 1 for the average case,but not the worst case of the fluid bed gasifier. It should be noted that the results presented herein for the rotary cyclone should be considered tentative until the vendor-supplied data employed in these assessments are confirmed. Uncertainties in the fractional efficiency data for the rotary cyclone are discussed in Section 4.

Since the particulate removal requirement of End Use 2 is not as restrictive as End Use 1, the number of control devices applicable to End Use 2 is increased considerably as compared to End Use 1. The results in Tables 21 and 19 show that both the fabric filter and the venturi scrubber are capable of achieving the requirements of End Use 2 for all gasifier effluents. The Aerodyne rotary flow cyclone was found to be applicable to all the gasifier effluents except for the worst-case fluid bed gasifier. However, with a conventional cyclone upstream as a scalping device, it would be applicable to this worst case as well. A conventional high efficiency cyclone by itself is found applicable to the best and average cases of the fixed bed gasifier, and the best case of the fluid bed gasifier. The CPC granular bed filter is found to have the same applicability as the high efficiency cyclone mentioned above. Two cyclones in series are capable of achieving the same efficiency as one Aerodyne rotary flow cyclone. A cyclone followed by a CPC granular bed filter would be applicable to two more cases than the CPC filter by itself, namely the average case of the fluid bed gasifier and the best case of the entrained bed gasifier. As for an electrostatic precipitator, it was found that a dry-type device is not applicable to fixed bed gasifier effluents. This is due to the fact that the particles in these effluents have very high carbon contents (55 percent to 80 percent), which results in low resistivity of the particles and inefficient collection. The electrostatic precipitator was found to be applicable to the best and average cases of the fluid and entrained bed gasifiers for End Use 2. With a cyclone upstream as a scalping device, the electrostatic precipitator would also be able to achieve the required removal efficiency for the worst cases of the fluid and entrained bed gasifiers.

As discussed previously, the applicability assessments presented herein are based only on the ability of the various control devices to meet specified particulate collection efficiencies. Other possible limitations such as economic feasibility, energy requirements, or operational reliability are not considered in these analyses. For example, a fabric filter could not be employed for gasifier effluents containing high levels of liquid or "sticky" particles. Thus, fixed-bed gasifiers, in particular, may not be compatible with fabric filters, due to the quenching operation commonly used to condense and remove tars and oils. As discussed in Section 2, the characteristics of the particulates in the gasifier effluents are generally not sufficiently well known to make such an assessment.

The results of the applicability assessments discussed above are summarized in Table 23.

TABLE 23 Summary of Applicability Assessments

	Applicability of Control Devices for Gasifier Types**								
	Fixed Bed			Fluid Bed			Entrained Bed		
End Use/Control Device	B	W	A	B	W	A	B	W	A
COMBINED-CYCLE									
conventional cyclone	-	-	-	-	-	-	-	-	-
rotary cyclone	X	X	X	X	-	-	X	X	X
venturi scrubber	X	X	X	X	-	X	X	X	X
fabric filter	P	P	P	X	X	X	X	X	X
E.S.P.	-	-	-	-	-	-	-	-	-
granular bed filter	-	-	-	-	-	-	-	-	-
rotary cyclone*	X	X	X	X	-	X	X	X	X
venturi scrubber*	X	X	X	X	X	X	X	X	X
fabric filter*	P	P	P	X	X	X	X	X	X
E.S.P.*	-	-	-	-	-	-	-	-	-
granular bed filter*	-	-	-	-	-	-	-	-	-
BOILER FUEL									
conventional cyclone	X	-	X	X	-	-	-	-	-
rotary cyclone	X	X	X	X	-	X	X	X	X
venturi scrubber	X	X	X	X	X	X	X	X	X
fabric filter	P	P	P	X	X	X	X	X	X
E.S.P.#	-	-	-	X	-	X	X	-	X
granular bed filter	X	-	X	X	-	-	-	-	-
rotary cyclone*	X	X	X	X	X	X	X	X	X
venturi scrubber*	X	X	X	X	X	X	X	X	X
fabric filter*	P	P	P	X	X	X	X	X	X
E.S.P.*	-	-	-	X	X	X	X	X	X
granular bed filter*	X	-	X	X	-	X	X	-	-

* A conventional cyclone is assumed to be employed as a scalping device upstream of the indicated primary control device.

** B - Best Case
W - Worst Case
A - Average Case
P - Designates probable inapplicability due to operating problems, although particulate removal is adequate.
X - Designates control device is applicable.

# ESP is not applicable to a fixed bed gasifier due to high carbon content and low resistivity of particles.

SECTION 6

FATE OF POLLUTANTS

In the previous sections, technologies for controlling the particulate and tar levels of the converter product gases have been discussed. Each control technology identified, in turn, generates solid, liquid, and/or gaseous wastes that also must be disposed of in a proper manner. In addition, precautions must be taken to prevent environmental damage resulting from the combustion of the product gas or tars.

To assess the pollution potential of controls and product/by product utilization, the "fate of pollutants" must be understood. Composition of waste and product streams must be quantified for trace elements, sulfur compounds, organics, and any other potential pollutants. By determining those streams in which certain pollutants tend to concentrate, and thus present potential pollution problems, proper disposal and control technologies can be selected to minimize environmental degradation.

The following discussion on the fate of these pollutants is based upon limited data from experimental and commercial installations obtained during various test programs. The data provide insight into where potential problems exist. However, due to the fact that most of the available data are preliminary and limited, caution must be taken in comparing data from different tests or assuming that information collected is necessarily representative of either a specific process or a generic type of gasifier.

It is well documented that coal contains a vast array of trace elements that are present in concentrations of less than 1%. During gasification, many of these elements may volatilize. Some, such as mercury, selenium, arsenic, molybdenum, lead, cadmium, beryllium and fluorine are recognized as toxic substances. Unlike the product gases of coal combustion, coal gasification takes place in a net reducing atmosphere. Volatile compounds such as carbonyls, hydrides, and sulfides are likely to be formed.

Jahnig (70) estimated the quantities of certain trace metals likely to be volatilized during coal gasification. His estimates are presented in Table 24 Assuming that these elements are carried overhead with the product gas, the potential magnitude of the problem can be realized. Thus, these volatilized elements must be collected and properly disposed of. If these contaminants should remain in the product gas when it is combusted, severe environmental consequences may occur.

Jahnig concluded that "the combined amounts of all volatile portions of

TABLE 24

TRACE ELEMENTS - ESTIMATED VOLATILITY (70)

	Hypothetical Coal ppm	% Volatile*	kg/day	(lb/day)**
Cl	1500	90+	25,000	(54,000)
Hg	0.3	90+	4.5	(10)
Se	1.7	74	23	(50)
As	9.6	65	110	(250)
Pb	5.9	63	67	(148)
Cd	0.8	62	9.1	(20)
Sb	0.2	33	1.4	(3)
V	33	30	180	(397)
Ni	12	24	52	(115)
Be	0.9	18	3.2	(7)
Zn	44	10	80	(177)
B	165	10	300	(660)
F	85	10	154	(340)
Ti	340	10	617	(1360)
Cr	15	nil		nil

---

* Volatility based mainly on gasification experiments but chlorine is taken from combustion tests, while zinc, boron, and fluorine were taken at 10 percent for illustration in absence of data.

** Estimated volatility for 1.8×10^7 kg/d (20,000 TPD) of coal to gasification.

trace elements can present a formidable disposal problem." Some of the volatile matter which is carried out of the gasifier with the raw product gas will be removed when the gas is cooled and scrubbed. Some compounds such as cyanides can be destroyed by recycling to the gasifier, but elements such as arsenic, chlorine, and lead cannot be recycled, and must be separated and recovered or deactivated prior to disposal.

Particulates collected by the various control technologies discussed in this report must be disposed of, or recycled in an economical and environmentally sound fashion. In some cases, these wastes will be in the dry solid form. In other instances, however, such as in the case of venturi scrubbers, the collected particulate matter is removed by a wet system. In such cases, the contaminated water may require treatment prior to discharge.

The particulate control technologies evaluated in this report include:

- venturi scrubber
- electrostatic precipitator
- conventional cyclone
- rotary cyclone
- fabric filter
- granular bed filter

Of these six technologies, only the venturi scrubber is not a dry process. The other five processes generally produce a dry, granular or powdery, solid waste. In the case of a venturi or other wet scrubber, the collected fly ash will be wet, complicating disposal of the ash while also necessitating wastewater treatment. Liquid waste streams from scrubbing or quenching operations must be treated prior to final disposal or discharge to surface or ground waters. Present and proposed regulations for liquid discharges generally require a high degree of water recycle and reuse within the plant, thereby minimizing the amounts of liquid to be released from the plant.

The collected ash, whether wet or dry, must be disposed of in a landfill or other environmentally acceptable manner. Undesirable elements can sometimes be leached from the collected particulate matter. Even if a dry collection system is used, the solid wastes will ultimately be exposed to leaching by ground water if they are disposed of as land fill or returned to the mine. Use of liners and entrapment of runoff and drainage water will minimize the likelihood of ecological degradation.

The standard technique for removing tars (as well as ammonia and some other pollutants) from the raw product stream is by quenching. The water that is used to quench the gas then becomes a gas liquor. This quench liquor cools the crude gas mixture to a temperature at which it is saturated with water. The gas liquor is then flashed and tar removed from the bottoms. The remaining water is then sent to water purification. The recovered tars can be used as a boiler fuel, incinerated, or sent to a landfill. It is unlikely that recovering of specific compounds, such as phenols, will prove to be an economically viable alternative.

The limited data on the fate of pollutants presented in this chapter does provide insight into the need for proper control techniques. Additional data is essential, however, in order to clearly define the fate of these pollutants.

6.1 FIXED BED GASIFIERS

The raw product gases from fixed bed gasifiers usually contain both tars and particulate matter. The ultimate fate of these pollutants is dictated by both the removal technology and the physical and chemical characteristics of the contaminants.

The standard technique for removing tars from the raw product gases is by quenching. The gas liquor and condensate produced is sent to the liquor treating area for separation of the tars (as well as other hydrocarbons, ammonia, carbon dioxide, and hydrogen sulfide). The gas liquors are cooled and, in the case of Lurgi, treated in three steps. The first step employs physical separation vessels for the recovery of the tars and tar oils present in the gas liquor. The second and third phases remove phenols, ammonia, and acid gases, respectively.

Table 25 shows the organic composition of quench liquor extract from a fixed bed gasifier (73). The high concentrations of phenolic compounds should be noted. Forced evaporation of large quantities of this spent quench liquor could cause emissions of significant amounts of organics into the atmosphere. Page (72) has reported that the concentration of sulfur in the by-product tar is dependent upon the nature of the coal feed stock. The sulfur concentration is two to three times greater in tar produced from lignite than from high volatile bituminous coal. It is probable that the sulfur content of the tar originating from bituminous coal would require SO_2 scrubbing of the flue gases resulting from the combustion of the tars. In this case, recycling of the tar to the gasifier or landfilling may be a more viable alternative.

Table 26 presents the trace element analyses of cyclone dust, quench liquor and tar. It can be seen that the concentration of Pb, Se, Cs and Fl were highest in the cyclone dust, while the Hg concentration was greatest in the tar. Table 27 compares the analyses of trace elements in the quench liquor with various water quality standards. Selenium concentration in the quench liquor is reported to be 400 times greater than the selenium standard for surface and intake water and approximately 80 times greater than the satisfactory level for irrigation water. Nearly all other elements equal or exceed Federal Water Quality Standards.

Even after initial treatment to remove oils, tar and other pollutants, the gas liquor will likely still contain small levels of heavy hydrocarbons, trace inorganics, and dissolved gases. This stream is, therefore, a potential pollution source, and may require further processing or disposal in solar evaporation ponds.

TABLE 25 ORGANIC COMPOSITION OF QUENCH LIQUOR - FIXED BED GASIFIER (73)

Fraction Number	% of Total Extract	Functional Groups Present
1	0.01	Aliphatic hydrocarbons
2	0.08	Alkyl-aryl hydrocarbons
3	0.22	Alkyl-aryl hydrocarbons, trace carbonyl, possible polycyclics or multi-substituted aromatics
4	0.76	Alkyl-aryl hydrocarbons, possible polycyclics, -OH present (possibly atmospheric moisture)
5	7.31	Phenol + alkyl/dialkyl phenols
6	74.18	Principally Phenol + other phenols
7	3.09	Phenols
8	8.34	Alkyl-aryl CH stretch, -OH, -C=O, Methyl Bending Vibration, Primary OH, possible inorganic sulfur + other ionic compounds

TABLE 26

TRACE ELEMENTS IN GRAB SAMPLES BY SSMS (73)

	Ash	Cyclone Bottom Dust	Quench Liquor	Tar
Uranium	56	--	--	--
Bismuth	0.4	<2	--	--
Lead	7	60	0.04	10
Mercury	NR	0.01	0.007	0.12
Barium	MC	460	0.1	27
Antimony	1	8	0.1	0.8
Cadmium	3	<2	<0.02	--
Molybdenum	22	14	0.06	1
Selenium	20	24	4	3
Arsenic	4	27	0.2	4
Zinc	26	85	0.07	7
Copper	540	130	0.1	3
Nickel	120	30	0.07	5
Chromium	510	90	0.03	3
Vanadium	MC	100	0.004	0.8
Titanium	MC	MC	0.05	29
Chlorine	230	720	0.3	6
Sulfur	250	MC	MC	520
Fluorine	56	270	2	22
Boron	130	70	2	19
Beryllium	22	6	--	0.1
Lithium	190	27	0.2	4

Note: All values expressed as ppm except liquor in which values are expressed as μg/ml.

MC = Major Component

TABLE 27

LEVELS OF TRACE ELEMENTS IN LIQUIDS FROM THE QUENCH LIQUOR AND BY-PRODUCT TAR VERSUS WATER QUALITY STANDARDS (73)

Element	Surface Water	Irrigation Water	Public Water Intake	Liquor μg/l	Tar ppm
Antimony	--	--	--	0.1	0.8
Arsenic	0.05	1.0	0.1	0.2	4
Barium	1.0	--	--	0.1	27
Beryllium	--	--	--	--	0.1
Boron	1.0	0.75	1.0	2.0	19
Cadmium	0.01	0.005	0.01	≤0.02	--
Chromium	0.05	5.0	0.05	0.03	3
Fluorine	--	--	--	2	22
Mercury	--	--	0.002	0.007	0.12
Lead	0.05	5.0	0.05	0.04	10
Manganese	0.05	2.0	0.00	0.03	0.9
Molybdenum	--	0.005	--	0.06	1
Nickel	--	0.5	--	0.07	5
Selenium	0.01	0.05	0.01	4	3
Vanadium	--	10.0	--	--	--
Zinc	5.0	5.0	5.0	0.07	7
Copper	1.0	0.2	1.0	0.1	3

The particulate matter collected from the raw product gases will have varying particle size distribution, bulk density, and ash and carbon content, depending upon the coal type and the gasifier operating conditions. Apparently the levels of organic compounds are much higher in the particulate matter than in the bottom ash. Approximately 400 ppm of organics have been found in the particulate matter, as compared with 20 ppm in the bottom ash. Table 28 indicates the organic composition of the cyclone dust. Table 29 indicates other characteristics of the particulate matter such as ash content, size and density.

Assuming a 7.1×10^3 m^3/day (250,000 scfd) production of medium Btu-gas, it is estimated that for fixed bed gasifiers, up to 4.5×10^4 kg (100,000 lbs) of flyash per day would be collected and then disposed of or recycled.

6.2 FLUID BED GASIFIERS

Several experimental studies (75,76,77,78) have been performed using the Pittsburgh Energy Research Center's (PERC) 10 cm (4-inch) diameter Synthane gasifier. Samples taken do provide some understanding of the fate of pollutants in fluid bed gasifiers. However, the extrapolation of pilot plant data to commercial scale situations must be exercised with caution. Also, the accuracy of the data is questionable as indicated by inconsistencies in material balances. Still, the data does give insight into the fate of the pollutants.

Table 30 shows the trace element analysis for a typical test run of the Synthane gasifier. Other runs performed during this study tended to substantiate these data. As can be seen, many of the trace elements tend to concentrate in the particulate and char. Some of the more volatile elements such as arsenic, lead, cadmium and mercury also are found in the tars in levels that are potentially harmful. Almost all of the chlorine concentrates in the water.

Analyses were performed on tars from various coals as shown below:

	Illinois #6	Illinois #6	Lignite
Carbon	82.6	83.4	83.8
Hydrogen	6.6	6.6	7.7
Nitrogen	1.1	1.1	1.0
Sulfur	2.8	2.6	1.1

This analysis is on a moisture and ash free basis.

Table 31 presents the organic analysis for the benzene soluble tar from the Synthane gasifier. Apparently, the tar is predominantly made up of napthalenes, acenapthenes, aromatics, and phenylnapthalenes.

6.3 ENTRAINED BED GASIFIERS

Data on the fate of pollutants from entrained bed gasifiers is somewhat

TABLE 28

ORGANIC COMPOSITION OF CYCLONE DUST EXTRACT FIXED BED GASIFIERS (73)

Fraction	% of Total Extract	Assignment
1	35.2	Paraffinic hydrocarbons, considerable branching
2	5.8	Paraffinic functional groups, traces of substituted aromatics
3	0.3	Split carbonyls, esters (formate or butyrate), methyl, isopropyl and tributyl branching, primary alcohols)
4	0.9	
5	1.0	Aromatics, carbonyls, aliphatic hydrocarbons
6	36.5	Split carbonyls; methyl, isopropyl and tributyl branching; secondary alcohols; esters, possible 5C ring lactones; branched cyclic alcohols
7	14.3	(No assignment made)

TABLE 29

CHARACTERISTICS OF PARTICULATES - FIXED BED GASIFIER (73)

	Collected by Cyclone			Not Collected by Cyclone		Suspended in Tar	
Coal Type	Average dp(μm)	Ash Content (wt%)	Bulk Density	Average dp (μm)	Ash Content (wt%)	Bulk Density	Average dp (μm)
Bit.	170	10.2	0.40	--	--	--	2-20
Bit.	95	15.4	0.53	20*	10.4	0.31	--
Anthr.	200	47.3	0.93	<1*	54.7	--	--
Lign.	70	23.0	--	--	--	--	--

* Agglomerated

TABLE 30

LABORATORY SYNTHANE GASIFIER
TRACE ELEMENT ANALYSIS OF ALL STREAMS (77)

Run # 162	Feed Coal PPM (µg/g)	Filter Fines PPM (µg/g)	Char PPM (µg/g)	Tar PPM (µg/g)	H_2O PPM (µg/g)
Ag	0.01	< 0.01	< 0.05	--	--
Al	>0.5	540	1800	29	0.007
As	0.87	3.7	6.5	0.71	0.001
B	86	64	380	12	43
Ba	170	130	98	3.6	0.10
Be	1.5	7.2	4.6	0.03	--
Bi	<0.10	<1.7	<0.44	0.20	--
Br	0.23	0.65	1.6	0.02	0.001
Ca	>1%	>0.5%	>1%	450	2.4
Cd	0.097	0.88	1.6	--	--
Ce	47	25	54	0.29	--
Cl	93	11	33	1.5	300
Co	14	17	95	0.09	0.002
Cr	170	47	240	7.1	0.043
Cs	0.26	1.2	0.65	--	--
Cu	39	70	40	0.74	0.003
Dy	1.4	3.9	1.6	--	--
Er	2.1	0.41	0.80	--	--
Eu	0.55	0.39	0.65	--	--
F	490	610	150	0.97	39
Fe	>1%	>0.5%	>1%	240	0.081
Ga	8.3	3.6	4.5	0.08	--
Gd	1.9	1.2	0.48	--	--
Ge	1.1	1.3	5.4	0.08	--
Hf	0.83	3.5	11	--	--
Hg	0.10	0.20	*	1.2	0.027
Ho	0.43	0.16	0.45	--	--
I	0.4	1.9	0.27	0.02	--
K	>1%	190	5400	14	0.31
La	22	6.7	17	0.03	--
Li	0.8	34	67	0.51	0.001
Lu	0.085	<0.18	0.40	--	--
Mg	2800	4600	3500	240	0.57
Mn	160	48	240	2.2	0.20
Mo	15	21	14	0.31	--
Na	1900	>1%	4700	360	6.6
Nb	4.7	7	13	0.08	--

Continued

TABLE 30 (Continued)

Run # 162	Feed Coal PPM (µg/g)	Filter Fines PPM (µg/g)	Char PPM (µg/g)	Tar PPM (µg/g)	H_2O PPM (µg/g)
Nd	23	19	11	0.06	--
Ni	43	12	25	1.2	0.018
P	130	460	460	14	0.04
Pb	0.55	2.2	21	0.22	0.003
Pr	7.3	7.5	4.2	0.02	--
Rb	180	36	27	0.10	--
S	>1%	7700	2100	120	1.6
Sb	0.18	0.04	1.9	--	--
Sc	5.3	6.4	17	0.02	--
Se	2.2	15	4.7	0.23	0.14
Si	>1%	>1%	>1%	500	2.8
Sm	2.7	0.30	0.86	0.01	--
Sn	0.6	0.75	1.9	0.03	--
Sr	3.3	44	70	4.5	0.12
Ta	0.73	0.64	1.2	--	--
Tb	0.2	0.20	0.89	--	--
Te	<0.29	<0.19	0.15	--	--
Th	3	5.8	4.3	0.06	--
Ti	880	1800	3300	8.4	0.003
Tl	<0.12	<0.19	<0.25	0.11	--
Tm	0.24	0.10	0.20	--	--
U	1.4	5.6	5.4	0.01	--
V	100	44	190	0.21	--
W	0.08	2.2	4.8	0.09	--
Y	21	37	48	0.10	--
Yb	0.35	2.7	2.2	--	--
Zn	25	11	100	0.48	0.13
Zr	10	22	28	0.26	--

* Insufficient results

TABLE 31

MASS SPECTROMETRIC ANALYSES OF BENZENESOLUBLE TAR FROM SYNTHANE GASIFIER VOL. % (76)

Structural type (includes alkyl derivatives)	Run HP-1 No. 92, Illinois[a] No. 6 coal	Run HPL, No. 94, lignite	Run HPM No. 111, Montana subbituminous coal	Run HP-118 No. 118,[a] Pittsburgh seam coal
Benzenes	2.1	4.1	3.9	1.9
Indenes	8.6[b]	1.5	2.6	6.1[b]
Indans	1.9	3.5	4.9	2.1
Naphthalenes	11.6	19.0	15.3	16.5
Fluorenes	9.6	7.2	9.7	10.7
Acenaphthenes	13.5	12.0	11.1	15.8
3-ring aromatics	13.8	10.5	9.0	14.8
Phenylnaphthalenes	9.8	3.5	6.4	7.6
4-ring pericondensed	7.2	3.5	4.9	7.6
4-ring catacondensed	4.0	1.4	3.0	4.1
Phenols	2.8	13.7	5.5	3.0
Naphthols	( )[b]	9.7	9.6	( )[b]
Indanols	.9	1.7	1.5	.7
Acenaphthenols	-	2.5	4.6	2.0
Phenanthrols	2.7	-	.9	-
Dibenzofurans	6.3	5.2	5.6	4.7
Dibenzothiophenes	3.5	1.0	1.5	2.4
Benzonaphthothiophenes	1.7	-	-	-
N-heterocyclics[c]	(10.8)	(3.8)	(5.3)	(8.8)
Average molecular weight	212	173	230	202

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[a] Spectra indicate traces of 5-ring aromatics.
[b] Includes any naphthol present (not resolved in these spectra).
[c] Data on N-free basis since isotope corrections were estimated.

more limited than that available on fixed or fluid bed gasifiers. However, in a study by Lee et al. (74),effluents from a high temperature entrained flow gasifier were analyzed. In this study, tests were run on an experimental gasifier. The authors report: "This gasifier is a pressurized, entrained-flow gasifier that has a capacity of 4.5×10^4g(100 pounds) of coal per hour,and has a downflow configuration with some similarity to an entrained flow gasifier operated by the Bureau of Mines during the period 1952-1963. It also has some similarity to the Texaco entrained flow gasifier configuration." In these tests a high volatile, non-caking Utah bituminous coal was used. Among the streams sampled were the scrubber effluent water and the gas evolved on depressurization of the scrubber water. The scrubber is used for final cleaning of soot and flyash particles. It follows a quench section, where molten ash droplets are solidified, and a heat exchanger.

Results of the test data are shown in Tables 32, 33 and 34 . Since only 0.45g (1×10^{-3} lbs) of organic material was found in the scrubber water, it is speculated that organics concentrated in the particulate matter. This was substantiated by a napthalene absorption test run by Brigham Young University, in which napthalene was added incrementally to scrubber water containing particulates. As shown in Figure 21, napthalene tended to be absorbed by the particulate matter. In terms of trace elements, apparently little or no Hg, Se or As was absorbed in the scrubber water. In the case of the scrubber flash gas, it should be noted that the total sulfur emissions are insignificant when compared with current EPA standards for SO_2 emissions from coal-fired boilers (1.2 lb/10^6 Btu).

For entrained bed gasifiers, total particulate collection will typically range from 1.8×10^5 to 1.6×10^6 kg/day (200 to 1800 tons/day) for a system producing 250,000 scfd of medium-Btu gas.

Oldham, et al. reported that typically, in the Koppers-Totzek process, the product gas passes through a venturi washer and gas cooler. The flyash scrubbed from the gas is removed as a 50 wt. % solids slurry from a clarifer. Both the solid and liquid phases of the flyash sludge contain trace elements. Ammonia, nitrates, sulfates and cyanides are all present in the sludge liquor. Polynuclear aromatic hydrocarbons in the gasifier product are also likely to condense in the venturi scrubber water and exit the scrubbing system with the flyash sludge (79).

TABLE 32 SCRUBBER WATER EFFLUENT INORGANIC SPECIES
ENTRAINED BED TEST GASIFIER (74)

Species	ppm	g/kg (lbs/ton of coal)
HCO_3^-	210	6.6 (3.3)
Cl^-	9.2	0.36 (0.18)
F^-	1.2	0.04 (0.02)
NO_3^-	0.4	0.02 (0.01)
NO_2^-	0.3	0.02 (0.01)

SO_4^{2-} and SO_3^{2-} detected at same level both before and after scrubbing

Carboxylic acids, phenols, and amines not detected

TABLE 33 SCRUBBER WATER EFFLUENT ELEMENTAL COMPOSITION

ENTRAINED BED TEST GASIFIER (74)

Element	ppm	g/kgx10^3 (lbs/ton of coal x10^3)
Ca	50	1880 (940)
S	6.0	240 (120)
Si	3.0	120 (60)
Fe	2.3	92 (46)
Cl	1.4	56 (28)
Zn	1.1	42 (21)
K	1.0	38 (19)
Sr	0.35	14 (7.0)
Cu	0.01	0.4 (0.2)

Ti, Mn, Ni, Br, Hg, Se, and As detected at same level both before and after scrubbing

Other Elements ($14 \leq Z \leq 40$) not detected (< 0.5ppm), where Z is the atomic number

TABLE 34 SCRUBBER WATER FLASH GAS COMPOSITION
ENTRAINED BED TEST GASIFIER (74)

FLASH GAS	g/kg of coal (lb/ton of coal)
CO_2	5.6 (2.8)
N_2	3.6 (1.8)
CO	3.6 (1.8)
CH_4	0.24 (0.12)
H_2S	0.058 (.029)
SO_2	0.042 (0.021)
H_2	0.016 (0.008)
HCN	0.0008 (0.0004)

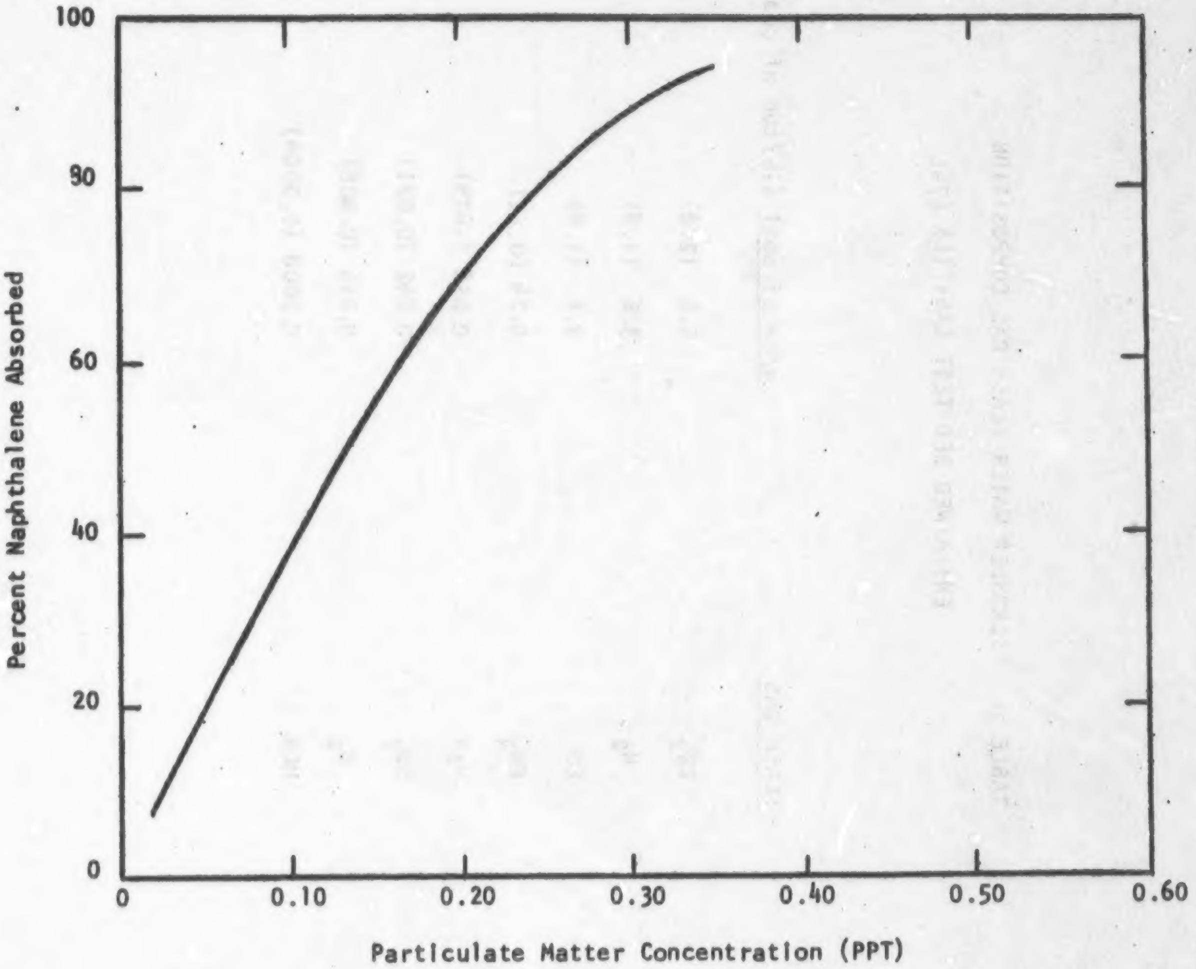

FIGURE 21. Absorption of Naphthalene By Particulates (74)

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